CIRCULATING COPY

TRANSPORT OF CONTAMINATED SEDIMENTS IN BOSTON HARBOR: FLUORESCENT TRACER STUDIES

Eric Adams, Keith Stolzenbach, et al.

MITSG 94-9

LOAN COPY ONLY

Sea Grant College Program
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Project Nos: 92-MCI-MF-1
89-RC-MCI-1

Related MIT Sea Grant College Program Publications

Analysis of Boston Inner Harbor dye study. E. Eric Adams, Drew L. McGillivary and Seung-Won Suh. MITSG 94-8. $10.

Representation of sources in a 3-D Eulerian-Lagrangian mass transport model. K. Nadia Dimou and E. Eric Adams. MITSG 92-6J. $1.

Flow cytometric detection and sizing of fluorescent particles deposited at a sewage outfall site. Kathleen A. Newman, Sheila L. Frankel and Keith D. Stolzenbach, [with] **Settling and coagulation characteristics of fluorescent particles determined by flow cytometry and fluorometry.** Kathleen A. Newman, Francois M. M. Morel and Keith D. Stolzenbach. MITSG 91-3J. $2.

Validation studies of models TEA and ELA in Boston Harbor and Mass Bay. E. Eric Adams, Douglas J. Cosler, John K. MacFarlane, Keith D. Stolzenbach, Philip M. Gschwend and Anne M. Okamura. MITSG 90-27. $5.

Mathematical simulation of pollutant transport in Boston Harbor. Richard F. Kossik. MITSG 87-3TN. $3.

Tracing and modelling pollution transport in Boston Harbor. Richard F. Kossik, Philip M. Gschwend and E. Eric Adams. MITSG 86-16. $5.

Please add $1 for shipping/handling and mail your check to :
MIT Sea Grant College Program, 292 Main Street, E38-300, Cambridge, MA 02139.

Transport of Contaminated Sediments in Boston Harbor: Fluorescent Tracer Studies

submitted to
Massachusetts Water Resources Authority

by

Eric Adams
Keith Stolzenbach
(Principal Investigators)

and

Joan Abbott
Daniele Agostini
Anne Canaday
John Caroli
Miriam Lawler
Jeng-Jong Lee
Denise Martin
Kathleen Newman
Xueyong Zhang
(Students)

MIT Sea Grant College Program
and
Dept. of Civil and Environmental Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

November 1991
(revised November 1992)

ACKNOWLEDGMENT

This study was sponsored by a Cooperative Research Agreement (No. 5964) between the Massachusetts Water Resources Authority (MWRA) and the Massachusetts Institute of Technology (MIT). Additional support and project administration were provided by the Coastal Processes Marine Center of the MIT Sea Grant College Program. This combined support is gratefully acknowledged.

The report represents one part of an interdisciplinary study entitled "Boston Harbor Study of Sources and Transport of Harbor Sediment Contamination: I—Transport of Contaminated Sediments in Boston Harbor" which has been conducted by researchers from MIT, the University of Massachusetts at Boston, and the MWRA. We would like to express our appreciation to individuals from UMass/Boston and the MWRA who collaborated with the data collection and analysis while conducting their parts of the study.

TABLE OF CONTENTS

I INTRODUCTION

This report documenting tracer studies is part of a larger, multi-disciplinary study entitled "Boston Harbor Study of Sources and Transport of Harbor Sediment Contamination: Transport of Contaminated Sediments in Boston Harbor." The larger study includes researchers from the Massachusetts Institute of Technology and the University of Massachusetts at Boston and aims to understand the transport of contaminated sediment in MWRA CSO, effluent, and sludge discharges within Boston Harbor and Massachusetts Bay. Specific activities include: 1) field tracer studies near outfalls (this report); 2) complementary measurement of suspended sediment and trace metal concentration at the same sites, plus Pb^{210} and trace metal analysis of nearby sediment cores; 3) modification and application of a fall cone device to measure the surficial strength from near bottom sediment cores; and 4) 2-D mathematical simulation of sediment resuspension and deposition within Boston Harbor, including estimates of net sediment flux between Boston Harbor and Massachusetts Bay.

The specific goal of the tracer studies was to better understand water column dispersion in near shore areas and to quantify the rate of initial deposition. During our project five fluorescent tracer studies were performed: three in Fort Point Channel and two in the Nut Island sludge discharge off of Long Island (see Figure 1). We also performed some settling column tests in the laboratory and analyzed results of an earlier dye study performed as part of the CSO Facilities Plan.

II FORT POINT CHANNEL SURVEYS

The majority of our effort was concentrated in Fort Point Channel. This site was emphasized, in part, because the CSO at the head of the channel (BOS070) is the largest in Boston Harbor. Fort Point Channel is also part of the inner harbor (hence several miles from beaches and shellfishing areas), and it it critical to future CSO planning to understand how dissolved and particle-bound pollutants discharged in the inner harbor are transported to the outer harbor. Finally the channel geometry and bridge crossings allow for easy sampling. On the other hand, BOS070 is perhaps the most complicated CSO because it receives combined sewer overflow from a number of different regulators as well as some storm water runoff. As such, direct monitoring of the aggregate overflow rate is very difficult and was not attempted.

Table 1 summarizes the three studies conducted in Fort Point Channel. During each study, fluorescent tracer(s) were discharged at the head of Fort Point Channel (mouth of BOS070 culvert) over a period of about two hours and monitored throughout the channel for about one week. Although dye injections were all made in the morning, the phase of the tide varied for the three surveys. Figure 2 plots tide levels in Boston Harbor during each study based on NOAA tide tables. Figure 3 plots hourly rainfall as measured at Logan Airport.

Monitoring was conducted by collecting discrete samples from bridges and the cha banks during intervals of about one to two hours surrounding low slack tide. During first two to three days of each study, surveys were conducted at each low tide, while during the latter phases, surveys were conducted at greater intervals. In the following graphs and discussion, sampling times are defined in terms of the number of tidal cycles after discharge, e.g., 1T, 2T, etc. Figure 4 shows typical horizontal positions used for dye sampling. Generally surface samples were collected at each station while vertical samples (1.5 m, 3 m, and 5 or 6 m) were also collected at the central stations.

For the first survey, the only fluorescent tracer was Rhodamine WT (a 20% solution of dissolved red dye, SG $\simeq$ 1.13 (depending on batch), available from Crompton and Knowles Corp., Charlotte, N.C.) and concentrations were detected using a Turner model 10 filter fluorometer with light source and emission and excitation filters appropriate for Rhodamine WT. During the second two surveys a mixture of Rhodamine WT and Saturn Yellow Day-Glo fluorescent paint was used. The paint is a 50% solution of suspended AX-17 pigment particles (SG of solution = 1.19; particle diameters range from 0.1 to 5 microns) manufactured by Day-Glo Corp. of Cleveland, Ohio. Choice of this tracer was guided by previous experience in using a similar paint of different color (Rocket Red, also manufactured by Day-Glo Corporation) in a field study of particle deposition in nearby Salem Harbor (Newman et al., 1990b). Settling and aggregation characteristics of the particles have been documented in Newman et al. (1990a). Fluorescent tracer samples were collected in amber bottles, brought to the laboratory where a surfactant was added, sonicated briefly to liberate tracer from the walls, and analyzed for tracer particles and Rhodamine WT using a fluorescence spectrometer (Perkin-Elmer). Exitation and emission wavelengths of 420nm and 506nm for the paint and 555nm and 575nm for Rhodamine WT were found to yield peak sensitivity and negligible interference between the two tracers. Dilution for both tracers was established by reference to laboratory standards corrected for background measurements. Note that our convention has been to define concentration and dilution of dye based on the original 20% solution while the concentration and dilution of paint is relative to pure AX-17 particles.

As shown in Table 1, several other tracers were monitored at times of low tide, including salinity (using a YSI model 33 SCT meter and the Seabird package aboard the UMass/B RV *Noridic*), fecal coliform and *Enterococcus* (by MWRA), and total suspended solids and metals concentration (by UMass/B personnel, described in a separate report). In addition, during the third study, surface and near-bottom measurements were taken near the channel mouth to better understand what fraction of pollution transported from the channel to the inner harbor on ebb tide returns with the following flood tide.

The following summarizes our understanding of transport processes in the channel as it progressed with each study.

2.1 November/December 1989 Study

General

This study involved the discharge of approximately 2.7 gallons (11 kg) of 20% Rhodamine WT dye. The dye was poured directly to the head of the channel in equal volume increments every ten minutes over the interval 0720 to 0850 on the morning of November 29 during flood tide (see Table 1). Tidal range at the time of discharge (defined for our purposes as the height of the nearest high water minus the height of the following low water) was 3.0 m, which is about average for Boston Harbor; the mean tidal range (mean high water minus mean low water) is 2.9 m (NOAA Tide Tables). Weather conditions prior to and during the study were essentially dry. (Logan Airport reported 0.11" of rain during November 28, but no rain fell during the study.) Eleven low tide surveys were conducted over six days as indicated in Table 1.

Dye Data

Figure 5 shows a typical longitudinal-vertical section of dye, indicating a pattern of circulation in Fort Point Channel in which water from upstream is dispersed longitudinally in the downstream direction and vertically into the deeper parts of the channel. The dye concentration becomes relatively homogeneous throughout the channel in about two days. The time variation of surface concentration is shown in Figure 6.

Two quantities of interest in pollution transport problems, which are often derived from dye studies, are the hydrodynamic residence time τ and the flushing rate k_f. If the dye were discharged continuously, and reached quasi–steady-state conditions (repeating each tidal cycle), τ could be defined by the total mass of dye in the channel divided by the rate of dye delivery,

$$\tau = \frac{\int c \, d\forall}{\dot{m}} \tag{1}$$

The flushing rate, k_f, would simply be τ^{-1}. Note that both k_f and τ are functions of dye discharge location.

For an instantaneous release, τ is defined by the first moment of the residence time distribution f(t) or

$$\tau = \frac{\int_0^\infty f(t) t \, dt}{\int_0^\infty f(t) \, dt} \tag{2}$$

If the amount of dye remaining in the channel is M(t), and the initial amount is M(0), then the total amount that has left, up to time t, is

$$\int_0^t f(t) dt = M(0) - M(t)$$

or

$$f(t) = -\frac{dM(t)}{dt} \tag{3}$$

Substituting Eq. (3) into Eq. (2) and simplifying yields

$$\tau = \frac{1}{M_0}\int_0^\infty M(t)dt \tag{4}$$

That is, τ is the zeroth moment of the time-varying distribution of total mass in the channel, divided by initial mass. For an instantaneous release, τ will be a function of the time (phase of the tide) as well as location of the tracer release. Note that, in order to perform the integration in Eq. (4), M(t) must be defined for all t. The tail of the distribution (large t) can be expected to decrease asymptotically making it difficult to distinguish from background.

Figure 7 shows the distribution of dye mass based on spatial integration of dye concentration measurements collected at low tide. The value of τ for this distribution, based on Eq. (4), is about 2.5 days, making the flushing rate $k_f \equiv \tau \simeq 0.4\ d^{-1}$. Note that the flushing rate has most meaning for a continuous discharge in which case k_f is the rate of mass removal that just balances the rate of injection. For an instantaneous discharge, the rate of removal is not constant as indicated in the semi-log plot of Figure 8 showing M(t)/M(0) vs. time. Because the discharge is to the head of the channel, the initial rate of removal (indicated by the absolute value of the slope of the graph) is slower than the subsequent rate. The difference is probably accentuated in this study because the dye was release[illegible]ing flood tide resulting in initial transport upstream into the culvert. For refe[illegible], a constant rate of $k_f = 0.4\ d^{-1}$ is indicated by the straight line in Figure 8.

Freshwater

Figure 9 plots a typical longitudinal-vertical section of salinity for this study indicating the presence of freshwater upstream. The deeper downstream sections display some vertical stratification which we suspect from subsequent studies may be largely due to the

Charles River (see discussion of May 1990 survey). Figure 10 plots the longitudinal variation of surface salinity over time. The measured salinities show a relatively time-invariant pattern with lower salinities at the upstream end of the channel. Estimating a background value for salinity of 29‰, the volume of freshwater within the channel is estimated as about 10^4 m^3. Combined with the estimated residence time of 2.5 days based on dye, we infer that there was a fresh water inflow of order 1 MGD during the time of the survey. Although very approximate, this value is consistent with earlier estimates of the dry weather flow from this CSO. Later communications from the MWRA indicated that, although all dry weather flows were supposed to have been eliminated at this site, there was a broken regulator during the time of the study.

Bacteria

The measured bacteria concentrations (see Figures 11 and 12) are similar to the dye measurements in that they were highest upstream and lowest in the deeper downstream samples with intermediate values in the surface layer downstream. Using bacterial loading rates obtained from concentration measurements at BOS070 and from the inferred freshwater inflow rate, and channel averaged bacteria concentration, a box model was used to compute first-order disappearance rates for fecal coliform and *Enterococcus*. Values fell in the range of 2–3 d^{-1}, but are very approximate due to uncertainty in bacterial concentrations at the culvert (including the effects of initial mixing), and inflow rate. Although significantly lower than many values reported in the literature, these values are close to the calibrated fecal coliform die-off rate of 2 d^{-1} used in the CSO Facilities Plan and based on bacterial measurements and modeling in Boston Harbor (CDM, 1989b).

2.2 May 1990 Study

General

From May 5 to May 15, 1990, we conducted our second tracer study in Fort Point Channel. The tracer solution consisted of 60 gallons of Saturn Yellow Day-Glo paint (about 130 kg of pure AX-17 pigment particles) mixed with 5.5 gallons (about 22 kg) of 20% Rhodamine WT (red) dye and about 340 gallons of ambient channel water in a pair of 250-gallon tanks. Tracer was delivered continuously through a hose across the culvert (BOS070) at the head of the channel for two hours (0800–1000) on Saturday morning May 5. High tide was at 0905 EDT. Tidal range at the time of discharge was 2.5 m, somewhat lower than average. As indicated in Table 1 nine low tide surveys were conducted over a period of ten days following tracer injection.

Freshwater

Beginning the previous night, and lasting throughout the tracer release, a total of 0.72" of rain was recorded at Logan Airport. Traces (< 0.01 inches/hour) were also reported throughout the day of the release. Figure 13 shows hourly rainfall measurements from Logan Airport and Figure 14 shows the computed discharge from BOS070 as predicted by the CDM sewer model (M. Heineman, personal communication). Note that these predictions use the revised sewer model calibrated against flow measurements at several of the regulators leading to BOS070 (BWSC, 1991). From Figure 14 we see that 3.6 million gallons were (predicted to have been) discharged over a period of about 14 hours, which represents about 1.5% of the low tide volume of Fort Point Channel. Although this volume is lower than previous estimates, there is reason to believe that the actual CSO discharge was even less. In their study, BWSC (1991) made measurements at three of the largest regulators tributary to BOS070 during ten storms from October 4 through December 28,

1990. Rainfall reported at Logan Airport was between 0.4 and 0.6" during six storms, 1.0 to 1.3" during three storms, and 3.91" during one storm (October 13, 14, 1990). Overflows were detected at one or more regulators during six storms (including the four largest), but tide gates prevented an actual discharge to the receiving water for all but the largest storm. Some flow was also discharged from the Union Park Pump Station which is tributary to BOS070. Meanwhile, comparison between measured discharge volume at each regulator and that predicted by the calibrated model shows good agreement for the large storm. However, for seven other storms, the model indicates a small discharge volume (ranging from less than 0.1 million gallons to 5 million gallons per storm for the three regulators combined) despite the fact that no discharge was observed during these storms (Table 9, BWSC, 1991).

During dye delivery for this study, an outward surface flow and low salinities were noted at the culvert, confirming that this was a wet weather event. Additional rain fell later in the study (May 10) but the five days immediately following the tracer delivery were dry. Figure 15 plots surface and bottom salinities at the outfall versus time. Surface salinity varied intermittently, including some values in the range of 10–15‰ (approximately half of the bottom salinity, indicating a freshwater discharge that receives an initial dilution of about two) and others nearly equal to the bottom salinity (indicating no freshwater flow). Low salinities (12–14‰) were observed during the tracer delivery, as expected, but they were also observed during three additional low-tide surveys between May 6 and 8. As indicated previously, no rain fell during this period, leading to the suspicion that there may still be dry weather overflows. Or, perhaps, the freshwater represents flow that was trapped by tide gates downstream from regulator weirs. At any rate, unlike the steady dry weather overflow inferred during the first study (inference based on nearly constant salinity near the culvert), discharge during the second study appears to have been intermittent, and not correlated with rainfall.

We have also analyzed the UMass/B salinity data, collected in the channel during afternoon low tide on May 5, 6, and 7, in an attempt to conduct a freshwater balance. The objective was to compare the residence time computed using freshwater as a tracer with the residence time computed based on dye (see below). In view of the fact that dye was introduced during the tail end of the (computed) CSO discharge during May 1990, there was concern that the dye might not have accurately tagged the CSO event and that the true wet weather residence time was actually shorter.

Figure 16 plots longitudinal-vertical sections of salinity on the first three days of the study and Figure 17 plots vertical profiles of freshness defined as

$$f = \frac{S_0 - S}{S_0} \tag{5}$$

where S is salinity and S_0 is a reference (end member) salinity. Note the strong vertical stratification (in contrast to the corresponding section for the first study shown in Figure 9) and the substantial influence of the Charles River, as seen by the low surface salinities and the high surface values of f at the downstream station during the first and third surveys.

While one could argue that the high freshness could, in principle, be flow discharged from BOS070, this is highly unlikely. For one thing, the low salinities at the mouth of the channel during the first survey were taken at around 1400 hours (low tide), only 5–16 hours after the predicted CSO discharge. A far more plausible source is the Charles River, whose distance from the Northern Ave. Bridge (about 2.7 km) is only 60% greater than that of BOS070 (about 1.7 km; see Figure 1). During May 4 and 5, the two sluices controlling the release of water from the Charles River basin were open for approximately two-thirds of the available time (during which basin elevation exceeded harbor elevation). Based on a daily average flow rate of 1000 cfs when both sluices are open, the estimated two-day flow was about 860 million gallons or over 200 times the predicted CSO volume. Combined with the fact that much of this release occurred prior to the CSO event, and hence had a greater opportunity to be transported throughout the inner harbor, these calculations strongly suggests that we are seeing substantial Charles River water in Fort Point Channel. This conclusion is further corroborated by computing the freshwater inventory in the channel. Using a value of $S_0 = 30.4\%$ (the highest measurement) yields freshwater volumes of 22, 9.3, and 11.2 million gallons within the channel during the three surveys. These estimates are up to six times higher than the predicted volume discharged from BOS070.

While the above calculations pertain to the May 1990 study, similar statistics apply to average conditions. In an average year, freshwater flow at the Charles River dam ranges from about 1.5 m^3/s in July–September to about 23 m^3/s in March, with an annual average of about 9.4 m^3/s (CDM, 1976). Meanwhile, according to the future no action conditions assumed in the CSO Facilities plan, the estimated annual average CSO discharge from BOS070 is 399 million gallons/year or about 0.046 m^3/s (Table 3, CDM, 1989a)—a factor of 200 less than the average Charles River flow of 9.4 m^3/s. And this ratio does not consider the contribution from the Mystic and Chelsea Rivers. Furthermore, there is evidence from recent CSO monitoring that the future no action condition may overestimate current overflow volumes (BWSC, 1991). We conclude from the above that it is not feasible, during most periods of time, to use freshwater as a tracer of BOS070 discharge.

Bacteria

Figures 18 and 19 plot fecal coliform and *Enterococcus* counts taken near the surface at the left and the right walls of the culvert (looking downstream). Trends for the two bacteria are fairly consistent, but note the significant variation in concentration between left and right, a distance of about 10 m! This may be due to the fact that the culvert conveys both stormwater and CSO flow; the latter should be relatively free of bacteria. Also note that the maximum coliform counts were about $2 \times 10^4/100$ ml which is more than an order of magnitude less than corresponding maximum dry weather counts observed at the culvert during the first study. If we assume a dilution of two, based on salinity measurements, then the actual discharge concentration could be as high as about $4 \times 10^4/100$ ml, but this is still one-and-one-half orders of magnitude lower than the predicted wet weather discharge concentration. (The predicted "future no action" concentration for BOS070 is about $10^6/100$ ml as reported in Table 3 of TM 4-4/5-4 of the CSO Facilities Plan, CDM, 1989a.) Comparison of Figures 18 and 19 with Figure 15 indicates that highest bacteria measurements occurred during the dye release (tail end of the CSO event) when salinity was low. However, at subsequent times it is difficult to detect much correlation (positive or negative) between salinity and fecal coliform. One would expect that low salinity (indicating CSO discharge) would correlate with high coliform loading, but since we don't have measured flow rates, it is not possible to relate coliform concentrations with loadings. And, unlike the first study, it is not possible to infer a freshwater inflow rate because of the strong temporal variation in salinity. However, Figures 20 and 21, which plot surface and bottom bacteria measurements down the axis of the channel, show that bacteria concentrations throughout the second study were significantly less than those measured during the first study (Figures 11 and 12), supporting the lower inferred loading.

A devil's advocate could hypothesize that the lower average bacterial concentrations during the second study were due to greater tidal flushing, but the hydrodynamic residence times for the two surveys were comparable (see below). Such an advocate might also try to explain the difference based on literature suggesting an increase in bacterial die-off with temperature; indeed, water temperatures during May were significantly warmer than those in Nov./Dec. (11 to 13° C vs. 4 to 6° C). Literature also suggests that sunlight is an even bigger factor in die-off and the May study was conducted within seven weeks of the summer solstice while the Nov./Dec. study was within three weeks of the winter solstice. At a latitude of 40°, the difference in clear-sky solar radiation is almost a factor of three. These factors notwithstanding, the biggest difference in bacterial concentration during the two studies was at the point of discharge—before die-off could be affected by temperature or sunlight. Hence we conclude that the order of magnitude difference in inflow concentration was real.

Dye and Paint

Figure 22 plots a representative longitudinal-vertical section of dye concentration while Figures 23 and 24 plot longitudinal surface concentrations of dye and paint versus time. For the first survey peak concentrations of both dye and paint are found in the middle of the channel (Dorchester Ave.) indicating that tracer discharged at the channel head during high tide has been advected downstream (but not out of the channel) and that relatively clean freshwater has taken its place at the upstream location. In several of the subsequent surveys, tracer concentrations increase along the channel axis which appears to be the result of the initial slug being transported downstream from the culvert. These observations contrast with the first study where dye concentration showed a monotonic decrease along the channel axis during most surveys (see Figure 6). We attribute this difference to the fact that, during the second study, dye was released at about high tide, allowing nearly six hours of ebb before it could reverse. Conversely, during the first study, dye was released during the flood tide, allowing the dye to mix upstream in the culvert before exiting on ebb.

Figures 25 and 26 plot total dye mass versus time, based on spatial integration of measured concentrations over the channel volume. Note that concentrations have been plotted for longer times than during the first experiment. Because we do not see a decrease in dye mass after about 150 hours, it appears that background fluorescence may be contributing the equivalent of up to about 2 kg of dye mass. Sensitivity to the assumed background is shown in the several curves shown in the semi-log plot of Figure 26. Using Eq. (4) with the dye distribution of Figure 25 and the initial mass of 22 kg, the computed residence time is 2.1 to 3.1 days, depending on the assumed background fluorescence (corresponding to 0 to 2 kg). Choosing an intermediate background value, the residence time of 2.6 days is comparable with the value of 2.5 days obtained during the first study. Note that the tidal range during the second study was smaller than during the first (2.6 m vs. 3.0 m) leading to a longer theoretical residence time. On the other hand, the tracer was released at high tide during the second study which would augment the tidal flushing. Further discussion of residence times in comparison with theoretical tidal prism estimates is provided in Section 2.4. Figure 26 indicates that the rate of dye loss is relatively constant throughout the experiment. This is in contrast to the first experiment which showed slower loss during the initial phases. Again, the difference is attributed to the timing of the dye release. The high tide release during the second survey allowed the dye to mix more effectively throughout the channel, leading to a more constant rate of removal. The flushing rate of 0.4 d^{-1}, corresponding to a residence time of 2.5 days, is shown in Figure 26 for reference.

Figures 27 and 28 show the mass of paint versus time. More so than the dye, the paint concentrations are sensitive to background fluorescence. Background fluorescence, as measured prior to the surveys, was subtracted from the concentration measurements used in the figures. However, based on the trend at later times, it appears that an increase in background fluorescence is accounting for the equivalent of between 0 and 20 kg of pa[illegible] As with the dye, these values are used as upper- and lower-bound estimates in the semi-log plot of Figure 28.

Comparison over time of the concentration of paint and dye (or their integration--mass) allows one to quantify the rate of deposition of paint. Defining the mass of paint and dye as M_p and M_d respectively, we can write

$$\frac{d}{dt}M_p = -k_s Mp - k_f M_p \tag{6}$$

$$\frac{d}{dt}M_d = -k_f M_d \tag{7}$$

where k_s is the net deposition (or settling) rate of paint and k_f is the previously defined flushing rate. If we assume that k_f is the same for paint and dye, then one can combine Eqs. (6) and (7) to derive

$$\frac{d}{dt}(M_p/M_d) = -k_s(M_p/M_d) \tag{8}$$

The net deposition rate can be computed from the difference in the paint and dye removal rates shown in Figures 26 and 28 or from Figure 29 which plots the ratio of M_p/M_d vs. time. (In Figure 29 the upper and lower bound estimates of background dye and paint mass are again given.) Using the latter approach, the slope of the graph indicates a deposition rate of between 0.1 and 0.5 day^{-1} with the higher value more representative of earlier time and the lower value representative of later time. These values are within the range of the hydrodynamic flushing rate ($k_f \equiv \tau^{-1} \simeq 0.4$ days) suggesting that about half of the paint is depositing within the channel and about half is being flushed to the inner harbor. These estimates are discussed further in Section 2.4. Using a water depth of 6 m, net deposition rates of 0.1 to 0.5 day^{-1} correspond to settling velocities of 0.6 to 2.4 m/d which are somewhat higher than the range of values found in earlier studies with similar tracers conducted in Salem Sound (Newman et al., 1990b). It is also above the general range expected for discrete settling. The interpretation of settling rates is discussed further in Section 2.5 in connection with laboratory settling column tests.

2.3 July 1991 Study

General

From July 14 through July 19, 1991, we conducted our third fluorescent tracer study in Fort Point Channel. The study involved the release of 30 gallons of Saturn Yellow Day-Glo paint (about 65 kg of pure AX-17 pigment particles) mixed with 5.5 gallons (about 22 kg) of 20% Rhodamine WT red dye and about 190 gallons of ambient channel water in a 250-gallon tank. (The amount of dye was the same as used in our May 1990 study while the amount of paint was half of the quantity used in May 1990.) The tracer was delivered through a hose in the center of the BOS070 culvert during ebb tide from approximately 0340 to 0555 on Sunday morning July 14, 1991. The tidal range during discharge was 4.1 m, considerably greater than average. A total of nine low tide surveys was conducted over a period of six days as indicated in Table 1.

Rain fell intermittently during the day Saturday, with heaviest rainfall between about 2000 and 2300 (during flood tide). (See Figure 3.) Logan Airport reported 0.52" during Saturday and early Sunday while our rain gauge (beaker) on site recorded about 0.8". Surface salinity measurements at the culvert ranged from about 18‰ at the beginning of dye release, to about 17‰ in the middle, to about 21‰ at the end of release (Figure 30). Bottom salinities at the culvert were about 26–27‰ suggesting that the freshwater was diluted about 2:1 with ambient channel water. The fact that salinity decreased and then increased implies we probably tagged the middle of the freshwater discharge. However, our experience from the May 1990 study and from observation prior to this study is that freshwater accumulates within the culvert (upstream of the opening) and exits over several succeeding ebb tides. As a result, it is not possible to tag the entire freshwater flow by releasing dye on ebb tide. Prior to the release, it had been nearly dry for about one week. Indeed, the total rainfall for July 1991 prior to July 13 (Saturday) was only 0.79", and most of that fell on July 1. Hence there should have been relatively little freshwater in the system due to rainfall runoff. On the other hand, this is peak boating season when lock usage at the Charles River Dam is greatest.

Figure 31 shows a typical longitudinal-vertical section of salinity during the third study. In contrast to the first two studies, this section indicates the presence of freshwater from both the head (BOS070) and the mouth (Charles River) of the channel. Further confirmation of the CSO event is provided by the bacteria data presented below.

Some evidence of the Charles River may also be seen in Figure 32 which plots a time series of near surface salinity measurements taken at Northern Ave. In general, lowest salinities are seen at low tide when freshwater from the Charles River would have extended further downstream, toward the mouth of Fort Point Channel. The correlation between salinity and tide appears stronger during the first three tidal cycles following tracer injection (and rainfall) than at longer times.

Dye and Paint

Figure 33 shows a typical longitudinal-vertical section of dye concentrations and Figures 34 and 35 plot measured dye and paint concentrations versus distance at various times. The shape of the distributions shown in Figures 34 and 35—especially during the first survey—is more like the second experiment than the first. Again, we attribute this to the timing of the dye release; release during ebb tide in the third study allowed much of the dye to reach the middle of the channel. However, during the third study, maximum concentrations were often found at the BOS070 culvert, indicating that some of the dye resided upstream in the culvert even at low tide. The magnitude of this effect was likely amplified by the extreme tidal range occurring at the start of the experiment.

Figures 36 and 37 depict the decline in integrated mass of dye over time. Unlike the second study, dye mass continues to decline with time, suggesting there has been no major problem with background. However, the maximum dye recovery (first survey) was only about 18 kg, about 20% less than the report of 22 kg. Using Eq. (4), and an initial mass of 22 kg, the computed residence time is 0.9 days; similar calculations based on an initial mass of 18 kg give 1.1 days.

Figures 38 and 39 depict the decline of integrated paint mass over time and Figure 40 shows the ratio of paint to dye mass over time. As with the second experiment, upper and lower bounds are provided based on uncertainty in background levels. Using average background levels, a deposition rate of $k_s \simeq 1.0\ d^{-1}$ is estimated, with perhaps a faster rate representing earlier time and a slower rate representing later time. Note that this deposition rate, as well as the flushing rate, is considerably higher than corresponding values computed for the earlier studies.

For approximately $3\frac{1}{2}$ tidal cycles, supplemental dye and paint samples were also collected at the channel mouth (Northern Avenue) in order to obtain an independent assessment of tidal flushing. A pump connected to a continuous flow fluorometer with strip chart recorder was in operation during portions of this period to monitor dye concentrations.

Figures 41 and 42 plot measured near-surface and near-bottom (6 m) dye and paint concentration versus time in comparison with tidal stage. Both two-hour data and tidally filtered data are presented (tides were removed with a centered 12-hour running average). Note that the filtered surface concentrations decrease monotonically in time, while the bottom concentrations show little or no increase with time. The slow rate of increase in bottom concentration suggests that little tracer has been transported from surface to depth. The two-hour data can be used to study the return of tracer (or other substances) from the inner harbor to the channel during flood tide. A strong tidal variation is observed, with higher concentration during ebb and low tide than during flood and high tide (as expected). However, the difference is somewhat less than might be expected considering the high flushing efficiencies implied by dye residence times. This factor, combined with the observation of incomplete vertical mixing, suggests at least a secondary role for estuarine-type circulation in the flushing of Fort Point Channel.

Bacteria

Figures 43 and 44 plot measured fecal coliform and *Enterococcus* levels near the outfall versus time. Unlike the second study, relatively high concentrations (several above 10^6 in the case of *Enterococcus*) were detected at the time of the discharge definitely suggesting a CSO event. Values at later times were two to three orders of magnitude lower. Figures 45 and 46 plot longitudinal distributions of bacterial concentration down the surface of the channel for five surveys. With minor exceptions, the data indicate a monotonic decrease in concentration with distance downstream and with time following release. Finally Figure 47 plots surface measurements of fecal coliform and *Enterococcus* versus time at Northern Avenue. Although the two sets of bacteria measurements are correlated with each other, there appears to be little correlation with the phase of the tide. The cause of the relatively high fecal coliform readings between 40 and 50 hours after dye release is uncertain, but could reflect an additional source.

The decline in bacterial concentrations over time can be used to estimate die-off rates. Using the geometric mean of the decreases of measured bacteria concentration at the various stations in Figures 45 and 46, over the 1-day interval of 1T to 3T, yields a die-off rate of between 1.0 and 1.5 d^{-1} for both fecal coliform and *Enterococcus*. This calculation accounts for the decrease in concentration due to flushing ($k_d \simeq 1\ d^{-1}$ based on dye data), but ignores vertical mixing (i.e., any decrease in bacterial concentration due to exchange with bottom water.

2.4 Summary of Residence Times and Calculated Contaminant Fluxes through the Channel Mouth

Table 2 summarizes residence times for the three surveys; during the first two surveys the time was about 2.5 days while during the last survey it was about 1.0 days. Due to uncertainty in background, errors in spatial integration, and other factors, the estimated uncertainty in each value should be considered as approximately ±25%. The large difference between the first two surveys and the last survey may be due to a combination of factors including the tidal range, the phase of the tide during tracer release, and freshwater inflow.

Tidal Mixing

The first factor can be assessed using simple tidal mixing concepts. The simplest model assumes tidal prism mixing whereby incoming water during flood tide is mixed completely with channel water and a fraction equal to the tidal prism divided by the high tide channel volume is flushed during ebb tide. The theoretical tidal prism flushing time assumes that none of the mixed water that exits during ebb returns during the following flood, so the theoretical tidal prism flushing time would be

$$\tau_{theo} = \frac{(H+a_0)T}{2a_0} \tag{9}$$

where a_0 is the tidal amplitude, H is the average channel depth at MWL, and T is the tidal period. Using $H \simeq 6$ m, $2a_0 \simeq 2.9$ m, and $T = 12.4$ hr yields a theoretical time of approximately 1.3 days. Note that the tidal prism method provides a lower bound for the flushing time (due to purely tidal processes) because it assumes complete mixing within the channel and assumes no return on flood. Also note that the time is approximately proportional to the tidal amplitude a_0. Other tidal mixing theories, such as the modified tidal prism technique of Ketchum (1951), assume mixing only over a segment of the channel that is proportional to the local tidal excursion. Such theories give longer residence times and predict that residence time is proportional to the square of the tidal amplitude. A similar quadratic dependence is obtained if one estimates a tidal dispersion coefficient, from dimensional considerations, as being proportional to a local tidal excursion squared divided by tidal period (Officer, 1976).

Table 2 includes rescaled residence times obtained by multiplying the observed times by the ratio of the actual tidal range during the experiment to the average tidal range in Boston Harbor (in line 4) and the ratio squared (in line 5). Note that the rescaled values show much less variation among experiments, reflecting the strong influence of the extreme tidal range during the third experiment. Rescaling the residence times still yields the longest time for the first experiment, which can be attributed to the fact that the tracer was released during flood tide and hence was initially (partially) trapped within the BOS070 culvert.

Rescaling also still yields the shortest time for the third study. This may be due to the fact that this was apparently the only survey with a substantial CSO flow at BOS070. Hence we could expect that density currents played a greater role in transport during this survey.

Density Currents

The relatively small freshwater inflow, compared with the channel volume or the tidal prism, as well as the intermittence of the inflow, precludes the establishment of a classical estuarine circulation in Fort Point Channel. However, it is possible to show that density currents can play a significant role in channel flushing. Consider Figure 48 and assume Fort Point Channel has a constant width W and length L. Assume that a volume v_0 of freshwater, with initial normalized density difference $\Delta\rho_0/\rho$ relative to the ambient, initially occupied a width W, length ℓ_0, and depth h_0 at the channel head such that $v_0 = W\ell_0 h_0$. Assume the channel is quiescent (no tides) and otherwise unstratified (no influence of Charles River). Over time, mixing between the freshwater and underlying seawater will result in a dilution S (S > 1) such that the density difference is reduced to $\Delta\rho_0/S\rho_0$. Meanwhile, the plume will spread seaward such that $W\ell h = Sv_0$. After an initial period of time, it can be expected that the primary force balance is between excess hydrostatic pressure and interfacial friction, or

$$\frac{\Delta\rho}{\rho}g\frac{h^2}{2} = \frac{f_i}{8}\left[\frac{1d\ell}{2dt}\right]^2 b \tag{10}$$

where $d\ell/dt$ is the rate of propagation of the front and f_i is an interfacial friction factor. With the above exceptions, Eq. (10) can be solved for the time needed for the front to reach a length ℓ or

$$t = \frac{0.1\ell^{5/2} f^{1/2} W}{\left[\frac{\Delta\rho_0}{\rho}gS\right]^{1/2} v_0} \tag{11}$$

Note that time decreases in proportion to v_0, implying that large events will flush faster (by density currents) than small events. If we compute the time at which 63% of the plume has spread out of the channel, then $\ell = eL$ ($e \simeq 2.7$). Taking W = 140 m, L =

1700 m, $\Delta\rho_0/\rho = 0.023$ (corresponding to an ambient salinity of 30‰), $g = 9.8$ m/s^2, $v_0 = 1.3 \times 10^4$ m^3 (the predicted inflow volume during the second study), $S = 5$ (corresponding to an average surface to bottom salinity difference after mixing of 6‰), and $f = 0.02$, yields $t \simeq$ 2.5 days, or about twice the theoretical (tidal prism) time for tidal flushing. The plume thickness at this time would be

$$h = \frac{S\,v_0}{WeL}$$

or about 10 cm, and the average velocity would be

$$\frac{1}{2}\frac{d\ell}{dt} \simeq \frac{eL}{t}$$

or about 2 cm/s. The Reynolds number $\mathbb{R}e$ based on the average velocity and four times the depth would be about 8000, and taking the interfacial friction factor f_i as 75% of the smooth wall Darcy-Weisbach factor (Harleman and Stolzenbach, 1972) gives $f_i \simeq 0.02$ as suggested.

The approximations in the above analysis are many. For example, we know that tides will affect mixing (and hence the effective value of f_i) and observations suggest that some dye is transported to the bottom waters over a depth of order 5 m rather than all residing in a thin surface layer. Also ambient stratification, resulting from other freshwater source such as the Charles River, will affect the density currents; indeed if sufficient freshwater resides in the inner harbor, it is even possible that a surface density current will propagate upstream in the channel rather than downstream.

These factors notwithstanding, the relatively short channel does suggest that density currents can play a role in transport. Other things being equal, that role will increase as the value of freshwater v_0 increases. (However, the counteracting influence of other freshwater sources will also increase as v_0 increases.)

Residence Time Distributions

Figure 49 plots the dye residence time distributions for the three studies using Eq. (3), making no correction for the variation in tidal amplitude. Since the area under each curve is unity, the mean residence time f: each study is the first moment of the corresponding curve. We can note that, if the channel were spatially well mixed, the residence time distribution would be $f(t) = e^{-t/\tau}$, while if there were plug flow, $f(t) = \delta(t-\tau)$—i.e., a spike at $t = \tau$. In general the shape of the residence time curves suggests mixing patterns between well-mixed and plug flow. Again we note that the curve for the first study peaks latest, reflecting the discharge during flood tide, while the curve for the last study peaks first and declines most rapidly, reflecting the rapid flushing.

Superimposed on the residence time curves are three "decay curves" of exp(-kt) for k = 0.5, 1.0, and 2.0 day^{-1}. Note that the second and third experiments suggested a deposition rate for solids in the general range of 0.25 to 1.0 d^{-1}, while we expect a rate of bacterial die-off in the range of 1.0–2.0 d^{-1}. The ratio of the time-integrated flux of suspended paint or live bacteria exiting the channel, in comparison to the quantity discharged, can be estimated as

$$F = \int_0^\infty e^{-kt} f(t)\,dt \qquad \text{(12)}$$

As an example, consider the second study with intermediate flushing characteristics. For $k = 0.5$ d^{-1}, we compute $F \simeq 0.45$; identifying $k_s = 0.5$ d^{-1} as the net deposition rate of paint suggests that 55% of the paint settles in the channel. For $k = 2.0$ d^{-1}, $F \simeq 0.15$;

identifying $k_d = 2\ d^{-1}$ as the die-off rate for bacteria suggests that 85% of the discharged bacteria are dying before they exit the channel.

2.5 Laboratory Settling Column Tests

From previous discussion it appears that the net deposition rate of paint particles over the second and third surveys was in the range of 0.25 to 1 d^{-1}. The question is whether these rates are faster than would be expected from discrete gravitational settling (Stokes settling). If so, the difference could indicate the presence in the field of other settling processes such as particle aggregation.

To explore this issue, several laboratory settling experiments were undertaken. Observations were made of the decrease in relative fluorescence over time in five columns containing water that varied in both origin and tracer concentration. In Columns A, B, and E normal tap water was used with tracer concentration respectively of 10^{-7}, 10^{-5}, and 10^{-1} g/g. In Columns C and D the tracer concentration was 10^{-3} g/g, but in Column D distilled water was used while in Column C the water came from Fort Point Channel. The water columns were 75 cm high, and started out from well-mixed conditions (i.e., homogeneous tracer concentration throughout each column). The water columns were sampled at 1, 5, 24, 50, and 96 hours after settling started, through ports located near the bottom, the middle, and the top of the water columns. Further details regarding the laboratory experiment set-up and observations are found in Martin (1990).

Results are shown in Figure 50, where column average fluorescence intensity, measured with our spectrofluorometer, is plotted versus time. Column average is defined by weighting the top and bottom ports by 25% and the middle port by 50%. Also shown are data from Newman et al. (1990a) (in brackets) and the range of rates observed in the field (solid lines). Except for Column A, all water columns showed monotonic decreases in fluorescence intensity. Column A showed an initial increase in fluorescence which we think might be due to the difficulties involved in measuring fluorescence at the relatively low concentration (10^{-7} g/g). For the remaining columns the rate of fluorescence decrease was somewhat faster than obtained by Newman et al. (1990a), based on experiments with a similar fluorescent paint (Rocket Red), but considerably slower than the range obtained in the field. The difference between laboratory and field rates seems to confirm that there is a difference between the settling process in the field and the one in the laboratory. It is also noteworthy that no significant difference was observed between Columns C and D which contained similar initial concentrations but different solvents. The fact that Column C with Fort Point Channel water did not settle faster seems to rule out the role of aggregation between paint particles and ambient particles in explaining the enhanced settling in the field. This leaves aggregation between paint particles and bottom (fluff layer) sediment as a likely cause of the enhanced settling in the field. This is the hypothesis set forth by Newman et al. (1990b) and Stolzenbach et al. (1992).

To compare the laboratory results with Stokes law, it is necessary to relate fluorescence intensity to tracer concentration. For most (dissolved) fluorescent tracers, the relationship is nearly linear and is determined using calibration curves generated from laboratory standards. However, it must be recognized that the fluorescence of paint particles is proportional to the particle diameter squared while concentration is proportional to particle diameter cubed. For a given initial particle size distribution, discrete settling results in an initial loss of the largest particles resulting in a more rapid decline in concentration than fluorescence. To account for this affect, a model was developed based on the initial particle size distribution measured by Newman et al. (1990a). Discrete settling was assumed for each size fraction at a rate proportional to the diameter squared. The coefficient of proportionality was left unknown, but assumed to be the same for each size fraction. At a given time, the particle size distribution was obtained from the observed relative fluorescence and used to compute the relative tracer concentration. Average fluorescence intensities were used, obtained by averaging the fluorescence of each column, excluding Column A, at each time. The result was an averaged concentration at four times (5, 24, 49, and 96 hours).

Average concentration, normalized by initial concentration, is shown in Figure 50. From this figure a time-averaged net deposition rate k was computed and compared to the one predicted by Stokes law based on the assumed particle size distribution. The experimental model coefficient was greater by a factor of 1.49 (i.e., settling in each size fraction was about 50% greater than predicted by Stokes). The discrepancy is not as large as it seems: it can in fact be caused by a difference of only 22% between assumed and actual particle diameter in each size fraction. Such a possibility is not unlikely, given that the range in particle diameters is 0.1 to 5 microns (Newman, 1990a).

In addition to normalized concentrations from the laboratory, Figure 51 also displays normalized paint mass from the field experiments. The mass of paint has been calculated from fluorescence rather than concentration measurements in order to test the hypothesis that particle aggregation governs settling. If particle aggregation plays a role, then settling may be independent of particle size, in which case concentration is directly proportional to fluorescence. This was the tentative conclusion of Newman et al. (1990b) regarding their experiment in Salem Sound and, based on Figure 51, appears likely in our case as well. However, we emphasize the sample variability and uncertainty due to background concentration; these underly the dye and paint mass measurements which form the basis of the inferred settling rates in the field.

2.6 Analysis of CH_2M-Hill Dye Data

As part of the CSO Facilities Plan, several dye studies were conducted near CSOs (CH_2M-Hill Team, 1990). Each involved an instantaneous dye release followed by monitoring for up to 10 hours. While not directly related to our project, the studies are of interest because they provide insight into the near field (short term) transport of dissolved constituents from CSOs. As such the data also provide a complement to our fluorescent dye studies which examine flushing on a larger scale (order of 1 week).

Table 3 summarizes the dye studies. Of the nine samples, six were conducted in marine waters, including a wet and a dry weather release at Tenean Beach, a wet and a dry weather release at Fort Point Channel, and two wet weather releases in the Chelsea River. In each case dye was released instantaneously and monitored for 5–10 hours after release using a combination of horizontal (near surface) and vertical measurements. The report appendix includes horizontal contour plots and vertical profiles.

The horizontal contours can be used to estimate longitudinal dispersion coefficients according to the formula

$$D = \frac{\sigma^2}{2t} \tag{13}$$

where σ^2 is the longitudinal plume variance and t is time. Data are not sufficient to compute σ precisely, but σ may be estimated as 25% of the plotted plume length. With this definition, and choosing a common time of $t = 6$ hours, estimates for D range from 0.3 m^2/s to 7 m^2/s with a geometric mean of 1.5 m^2/s (see Table 4).

It is noteworthy that, for Neponset River, the wet weather coefficient is substantially greater than the dry weather coefficient while for Fort Point Channel, the wet and dry weather coefficients are similar. However, it is not clear how much—if any—freshwater flow actually occurred during the "wet weather" event. On Sept. 26, Logan Airport reported 0.62" of rain (mainly in the morning) while Blue Hills Observatory reported 0.88"; however, no rain was reported at either station for the remainder of the month. At any rate *our* field data for Fort Point Channel (collected over a time scale of a week rather than 6 hours) indicate greater flushing during the third study, which was the one conducted during greatest freshwater inflow.

It is possible, in principle, to compute corresponding lateral dispersion coefficients but the data, in general, do not include sufficient lateral resolution. However, looking at the plotted contours, it is clear that lateral dispersion coefficients would be about an order of magnitude smaller than longitudinal coefficients. Horizontal average coefficients, often taken as the geometric mean of lateral and longitudinal coefficients, would hence be somewhat less than 1 m^2/s. It is noteworthy that a value of 1 m^2/s was used for the puff dispersion coefficient in the ELA calculations for the CSO Facilities Plan (CDM, 1989b).

Vertical profiles show significant vertical stratification in dye concentration; hence presumably salinity and the various CSO constituents would also be stratified. This observation is certainly consistent with measurements taken during the first tidal cycle of our May study. However, our data indicate that concentration profiles became more uniform vertically after successive tidal cycles.

2.7 Summary and Conclusions

Based on our three tracer studies, and related data, we can draw the following conclusions.

Freshwater flow

• Fort Point Channel exhibits both vertical and horizontal salinity stratification. Horizontal gradients reflect freshwater inflow at the head (BOS070) and often at the mouth. Dye measurements show generally consistent spatial trends.

• Salinity measured at the culvert varies with time and is often not well correlated with rainfall. (Freshwater outflow has been observed at BOS070 several days after any rainfall.). This could reflect dry-weather overflows (as was the case during the first survey), or the discharge of freshwater trapped within the culvert downstream from regulators.

• Although freshwater flow measurements were not made, predicted freshwater inflow is small compared with channel volume. A storm value equal to about 1.5% of low tide channel volume was predicted for 0.72" of rainfall during the second study. While this inflow is too small (and intermittent) to allow establishment of classical estuarine circulation, resulting density currents do contribute to flushing.

• The annual average predicted CSO inflow rate is small (~.5%) compared with the corresponding discharge rate from the Charles River. This dichotomy makes it difficult, during most periods of time, to use freshwater as a tracer in the channel.

Transport of dissolved substances

• Residence time distributions, based on dye discharged at the BOS070 culvert, were developed for the three studies from the time variation of total dye mass in the channel. Calculated residence times were about 2.5 days for the first two studies and 1 day for the third. The shorter time for the third study can be attributed to the abnormally high tidal range, the timing of the tracer release (ebb tide), and the greater freshwater inflow through BOS070.

• Channel flushing is governed primarily by the tide, as suggested by the relatively short tidal prism residence time (~1.3 days for an average tidal range). The efficiency of tidal flushing increases with tidal amplitude and with discharges released during ebb or high tide.

• Freshwater inflows create density currents which help flush pollutants from the channel. The flushing rate increases with the volume of freshwater inflow. For the predicted inflow resulting form the 0.72" rainfall during the second study, a theoretical residence time (due only to density currents and neglecting other sources of stratification) of about 2.5 days is calculated.

• Freshwater from the Charles River, residing in the inner harbor at the mouth of Fort Point Channel, may improve flushing efficiency by transporting away pollutants that leave the channel during ebb and preventing their return on the following flood tide. On the other hand, hydrostatic pressures due to freshwater in the inner harbor oppose the action of density currents and may even lead to reverse circulation (near surface flow upstream in the channel).

Bacteria

• Bacteria loading, like freshwater, depends on rainfall and tide. Regarding bacterial pollutographs, it appears that we experienced three different regimes in our three studies. During the first study, under essentially dry weather conditions, a small constant loading was observed for nearly a week, suggesting a dry weather overflow. During the second survey, loading was small and intermittent, suggesting that one or more regulators had overflowed but that discharge to the channel was impeded by the tide gates. During the third study, a substantial, one-time loading was inferred. The possibility of different loading regimes should be considered when modeling the receiving water impacts from CSOs.

- We were able to use MWRA bacterial measurements during the first and third studies, combined with flushing characteristics for the dye, to compute die-off rates of order 1–3 d^{-1} for both fecal coliform and *Enterococcus*. Although there are significant approximations in these estimates, they are similar to the value of 2 day^{-1} found by CDM (1989b) in their calibration against Boston Harbor fecal coliform measurements in July 1988.

- Combining coliform die-off rates with the residence time distributions inferred from dye measurements allows us to calculate the fraction of bacteria which are transported alive out of the channel. For example, choosing a die-off rate of 2 day^{-1} and the second study (with intermediate flushing characteristics), approximately 15% of the bacteria are transported out of the channel where they may possibly impact downstream receptors.

Particle Deposition.

- Based on the relative disappearance of paint pigments and dye during the second and third studies, we infer a net deposition rate for paint of 0.25 to 1 d^{-1}. The rate was faster for the third study than the second and generally faster over short time (up to two days following discharge) than longer times.

- Combining net deposition rates for paint with the residence time distributions inferred from dye measurements allows us to calculate the fraction of paint particles that are transported out of the channel. For example, using a rate of 0.5 d^{-1} with the second study, approximately 45% of the particles would be transported out of the channel where they may possibly impact downstream receptors. Noting that the aggregation efficiency of pigment particles is less than that of CSO particles suggests that the flux of CSO particles, and their associated toxic contaminants, will be somewhat less.

• Deposition rates inferred from the relative disappearance of paint and dye are being compared with UMass/B measurements of historical deposition rates (^{210}Pb) and metal inventories compared with estimated CSO loadings.

• The particle removal rate is greater than that expected from discrete settling. Furthermore, laboratory settling column experiments showed no dependence of settling rate on paint concentration or solvent (distilled water vs. ambient channel water). Together, this evidence suggests that the particle deposition in the field could be caused by aggregation of paint particles with bottom sediments in the channel, a mechanism suggested by Newman et al. (1990b) and Stolzenbach et al. (1992). This mechanism would be enhanced in the upstream portion of Fort Point Channel by the rapid vertical transport due to tidal oscillation, which allows the more highly concentrated surface water to periodically contact the bottom sediment. This hypothesis is supported by the fact that the net deposition rate (as well as the flushing rate) was greater during the third study which had the large tidal range.

III NUT ISLAND SLUDGE PLUMES

Two additional fluorescent tracer studies were conducted at the site of the Nut Island sludge outfall at the northern tip of Long Island (see Figure 1). Each involved the ꞏ livery of Rhodamine WT dye into a sump at the Nut Island treatment plant, in such a ꞏ that it would be well-mixed by the time it reached the outfall 4.2 miles away. A primary objective of the experiment was to collect samples in the harbor and measure the relative concentration of dye and total suspended solids (TSS) over the following 8-10 hours. Any decrease in the ratio of TSS to dye could be attributed to settling of solids which would allow one to infer the area of initial deposition.

3.1 July 1980 Survey

The first Nut Island sludge survey was conducted on July 30, 1990. During the study, 11 gallons (about 44 kg) of Rhodamine WT dye were dispensed uniformly between 0600 and 0800 EDT into a sump at the Nut Island Treatment Plant. From there it was pumped into the outfall pipe along with sludge using a 9000-gph piston pump. Additional sludge was pumped into the pipe using a second 9000-gph piston pump. The timing of the dye release was chosen in anticipation of seeing it arrive at the outfall on ebb tide. (High tide was at 0611 EDT.)

Unfortunately, the experiment was unsuccessful on two counts. First, it was intended for the dye and sludge to be discharged simultaneously (i.e., from 0600 to 0800). However, one of the sludge pumps had been pumping since 0400. Hence the initial sludge arriving at the outfall was "unmarked." Second, whereas the dye was expected to arrive at the site between 0830 and 0900, nothing was observed until about 1400 (during flood tide!) when sludge first arrived. Dye arrived about an hour later (1500). Both sludge and the later sludge/dye mixture appeared very patchy. The reason for the delay in sludge and dye is not known.

Despite these factors a number of samples were collected using the UMass/B RV Noridic and analyzed. Seven samples were taken representing background conditions (prior to 1400) and conditions within the boil prior to observance of dye (1400 to 1500). Eight samples were collected near the boil during dye observance (1515 to 1545) and eight samples were collected downstream (west) of the boil (1610 to 1700).

Dye and suspended solids concentration were compared in the latter two sets of measurements. See Figure 52 and 53. Although there is a positive correlation, there is significant scatter, especially in the last set, which may be attributed to the patchy discharge conditions.

Dye concentrations downstream from the outfall are contoured in Figure 54. Although based on only eight measurements, they do show the plume extending along the southern side of President Roads and the northern end of Spectacle Island.

3.2 October 1990 Survey

On October 30, 1990, the experiment was repeated. Again 11 gallons (approximately 44 kg) of Rhodamine WT were dispensed uniformly into the sump at the Nut Island Treatment Plant and pumped with sludge into the outfall pipe between the hours of 0540 and 0740 EST. The second sludge pump as well as two centrifugal effluent pumps were also operating at this time. Hence the pipe contained a uniform mixture of effluent sludge and dye. The dyed sludge was first noted at the site at between 0810 and 0815 and appeared well mixed (no patchiness) to the eye. High tide occurred at 0739 EST.

Sampling was conducted by personnel from Battelle Ocean Sciences using the RV *Surveysa.* (Battelle was used because of their involvement in ongoing studies.) Sampling consisted of making vertical profiles and horizontal transects during which turbidity and dye fluorescence were continuously recorded along with salinity, temperature, pressure, and chlorophyll fluorescence. Seventeen water samples were also collected for analysis for dye (MIT) and TSS and metals (UMass/B). These included eight samples near the boil during the period of sludge release and nine samples collected throughout the plume after the sludge stopped.

As a first step in data analysis, an average dye concentration within the sludge outfall of 92 ppm was computed based on the dye delivery rate, and the effluent/sludge flow rate computed from the outfall volume and the dye arrival time. An average suspended solids concentration of 7100 ppm was computed by prorating the flow of sludge (assumed 2% solids content) and effluent (~0% solids content). These values were then used to compute the dilution of dye and solids in the receiving water using the formulae

$$S_d = \frac{C_{do}}{C_{do} - C_{db}} \tag{14}$$

$$S_s = \frac{C_{so}}{C_s - C_{so}} \tag{15}$$

where S stands for dilution and subscripts d, s, o, b refer to dye, solids, pipe, and background. Figure 55 shows the results using values of $C_{sb} = 2$ ppm and $C_{db} = 0$.

Several things can be noted from Figure 55. First, dilution near the boil (samples 1–8) ranges from about 150 to 1000 and is similar for dye and sludge, as it should be since the solids have not had time to settle. Note that data for samples 1 and 2 should be discounted because they were at the leading edge where dye concentration may not yet have been uniform. The lowest dilution value (150) is somewhat higher than the estimate of about 40 for centerline dilution based on EPA (1985) initial mixing models assuming a point source in a non-stratified, stagnant ambient. It also exceeds the estimates of 50–100 based on salinity measurements reported by Battelle (1989). The reason could be that none of our measurements, although taken *near* the boil, actually captured the peak concentration. It is also probable that dilution from the Nut Is. sludge outfall is greater than predicted for a single point source in a stagnant ambient.

The remaining nine samples, collected within the plume, show dilutions in the general range of 10^4 to 5×10^5. Assuming a near field dilution of 150:1 this represents a further reduction of concentration of 600 to 3000 fold. It is doubtful if all of this represents actual mixing; again a portion could be due to the fact that samples were not collected squarely within the plume. (To some extent this was intentional; for example samples 9–13 were intended to represent a section measured across the plume.)

Although the data appear to be valid, the large dilutions make an analysis of the relative concentration of dye and solids very sensitive to the assumed background value for solids. Assume that settling results, at some time, in a "true" solids concentration (relative to pipe concentration and accounting for background), which is a fraction ϵ less than the corresponding dye concentration, i.e.,

$$\frac{C_s - C_{sb}}{C_{so}} = \frac{1 - \epsilon}{S} \tag{16}$$

where the dilution S is based on dye. Hence

$$\epsilon = 1 - \frac{C_s - C_{sb}}{C_{so}} \cdot S \tag{17}$$

For example, assume $C_{so} = 7100$ ppm, $C_{sb} = 2$ ppm, $C_s = 8.39$ ppm, and $S = 10^3$, giving $\epsilon = 0.1$ (i.e., 10% of the solids have been removed in comparison with dye). An uncertainty in C_{sb} of ±0.1 ppm would yield a corresponding uncertainty in ϵ of ±0.014 or 14% of the nominal value of ϵ (an acceptable uncertainty). But now assume $S = 10^4$ and $C_s = 2.639$ ppm, again yielding a nominal value of $\epsilon = 0.1$. Now an uncertainty in C_{sb} of ±0.1 ppm yields an uncertainty in ϵ of ±0.14 or 140% of the base case (i.e., $-0.04 < \epsilon < 0.24$). For $S = 10^5$ the sensitivity is an order of magnitude worse still. We conclude that, with the available high dilution data, our "signal-to-noise ratio" is too weak.

The additional data collected by Battelle (1991) were also reviewed. These consisted of 34 transects near the boil between about 0907 and 1515 on October 30. Time series measurements of light transmission and dye fluorescence during each transect were converted to time series plots of suspended solids concentration and dye concentration respectively using the 17 discrete samples as standards (e.g., Figure 56). The time series were then digitized to create a scatter plot of suspended solids versus dye concentration. (For example, Figure 57 corresponds to Figure 56.) Typically, each transect yielded several hundred paired measurements. In principle, the slope of a best fit line passing through the origin could be established for each transect and plotted versus elapsed time. Elapsed time represents time after discharge and would be estimated as the distance from the plume divided by ambient velocity (for measurements during dye release) or time since the middle of the dye release (for more distant measurements taken later in the day).

Unfortunately, several circumstances prevented this procedure from being implemented accurately: 1) as discussed above, the background solids concentration (identified here as the spatially uniform concentration at the edges of each transect) seems to have changed dramatically with time from a value near 4 mg/l in the morning to about 2 mg/l in the afternoon; 2) the automatic scaling option was in effect on the flow-through fluorometer resulting in frequent scale changes and hence the loss of data until the fluorometer re established equilibrium; 3) small apparent offsets in time between the time series of TSS and dye (see Figures 56 and 57); and, perhaps most importantly, 4) no usable data after about 1100. Based on time of travel estimates, most data pairs represent travel times within the plume of one-half hour or less—insufficient to gauge reduction in solids due to deposition.

In retrospect, factors 2) and 4) could be corrected if the experiments were to be repeated and compensation could be made for factor 3). However, at this point the biggest uncertainty is factor 1), the large apparent variability in TSS background concentration.

IV REFERENCES

Battelle Ocean Sciences. 1989. A pilot study of the Deer Island and Nut Island sewage outfalls within Boston Harbor June 8–9, 1989. Final report submitted to MWRA.

Battelle Ocean Sciences. 1991. Field studies of Nut Island sewage plumes and background water properties in Boston Harbor October–November 1990.

Boston Water and Sewer Commission (BWSC). 1991. CSO monitoring report, Fourth qtr. 1990.

Camp Dresser & McKee (CDM). 1976. An evaluation of the removal of salt water from the Charles River Basin. Report prepared for the Metropolitan District Commission.

Camp Dresser & McKee (CDM). 1989a. Combined sewer overflow facilities plan. Technical memo 4-4/5-4. Sewer system modeling and receiving water modeling for no-action alternative.

Camp Dresser & McKee (CDM). 1989b. Combined sewer overflow facilities plan. Technical memo 5-32. Receiving water model calibration.

CH_2M-Hill Team. 1990. Boston Harbor combined sewer overflow dye study. Report submitted to MWRA.

Harleman, D. R. F., K. D. Stolzenbach. 1972. Fluid mechanics of heat disposal from power generation. *Annual Review of Fluid Mechanics* 4:7–32.

Ketchum, B. H. 1951. The flushing of tidal estuaries. *Sewage and Industrial Wastes* 23:198–209.

Martin, D. 1990. Summer Research 1990.

Newman, K., F. Morel, K. Stolzenbach. 1990a. Settling and coagulation characteristics of fluorescent particles determined by flow cytometry and fluorometry. *Environ. Sci. Technol.* 24(4):506–512.

Newman, K., S. L. Frankel, K. D. Stolzenbach. 1990b. Flow cytometric detection and sizing of fluorescent particles deposited at a sewage outfall site. *Environ. Sci. Technol.* 24(4):513–519.

Rex, A. J., et al. 1992. The state of Boston Harbor: 1991. Technical Report 92-3, Environmental Quality Department, Massachusetts Water Resources Authority.

Stolzenbach, K., K. Newman, C. Wang. 1992. Aggregation of fine particles at the sediment-water interface. *J. Geoph. Res.* (in press).

Officer, C. B. 1976. *Physical oceanography of estuaries and associated coastal waters.* New York: John Wiley & Sons.

US EPA. 1985. Initial mixing characteristics of municipal ocean discharges, Vols. 1, 2. Report No. EPA/600/3-85/073a, b. Environmental Research Lab, Narragansett, R.I. 02882.

Table 1

Fort Point Channel Surveys

Date of discharge	Nov 29, 1989	May 5, 1990	July 14, 1991
Time of discharge	0720–0850	0800–1000	0340–0555
Time of nearest high tide (phase during delivery)	1128 (flood)	0905 (high slack)	0124 (ebb)
Tidal range (m)	3.0	2.6	4.1
Rainfall at Logan Airport	0.11"	0.72"	0.52"
No. surveys/duration	11 over 6 days	9 over 10 days	9 over 6 days
Tracers			
dye	×	×	×
paint		×	×
salinity	×	×	×
bacteria (MWRA)	×	×	×
SS (UMass/B)		×	×
metals (UMass/B)		×	×

Table 2

Summary of Residence Times

	Nov. 1989	May 1990	July 1991
Time τ (days)	2.5	2.6	1.0
Tidal range $2a_0$ (m)	3.0	2.6	4.1
Tidal phase	flood	high	ebb
Rescaled time $\tau(a_0/\bar{a}_0)$ (days)	2.6	2.3	1.4
Rescaled time $\tau(a_0/\bar{a}_0)^2$ (days)	2.7	2.1	2.0

Table 3

Dye Release Data for Each Dyes Study
(adapted from CH_2M-Hill Team, 1990)

Date	Location	Weather	High tide (EST)	Time of release (EST)	Tidal phase at rel.	Amount of dye (gal)	Release point
9/14/89	Tenean Beach	dry	9:45	9:43	high	4	end of outfall
9/18/89	Alewife Brook	dry		13:20		0.25	Mystic Valley Parkway Bridge
9/25/89	Fort Point Channel	dry	7:45	10:12	ebb	4	end of outfall
9/28/89	Fort Point Channel	wet	10:07	11:30	ebb	4	end of outfall
10/2/89	Tenean Beach	wet	0:15 12:23	4:45	ebb	4	end of outfall
10/17/89	Winnisimmet and Ferry—Chelsea River	wet	12:28	12:00	high	4	manhole upstream of outfall
10/19/89	Winnisimmet and Ferry—Chelsea River	wet	14:18	12:15* (16:30)	 ebb	4	manhole upstream of outfall
10/30/89	Arsenal Street Bridge—Charles River	wet		19:33		2	manhole upstream of outfall
11/3/89	Stony Brook—Charles River basin	wet		6:50		4	gatehouse upstream of outfall

Table 4

Computed Longitudinal Dispersion Coefficients for Dye Experiments Reported in Table 3

Site	Weather	D (m^2/s)	Figure*
Chelsea R.	wet	6.9	CH-W1-3
Chelsea R.	wet	1.1	CH-W2-2
Fort Point Chan.	dry	1.3	FP-D-2
Fort Point Chan.	wet	1.7	FP-W-3
Neponset R.	dry	0.3	TN-D-7
Neponset R.	wet	2.2	TN-W-2

*from CH_2M-Hill Team (1990)

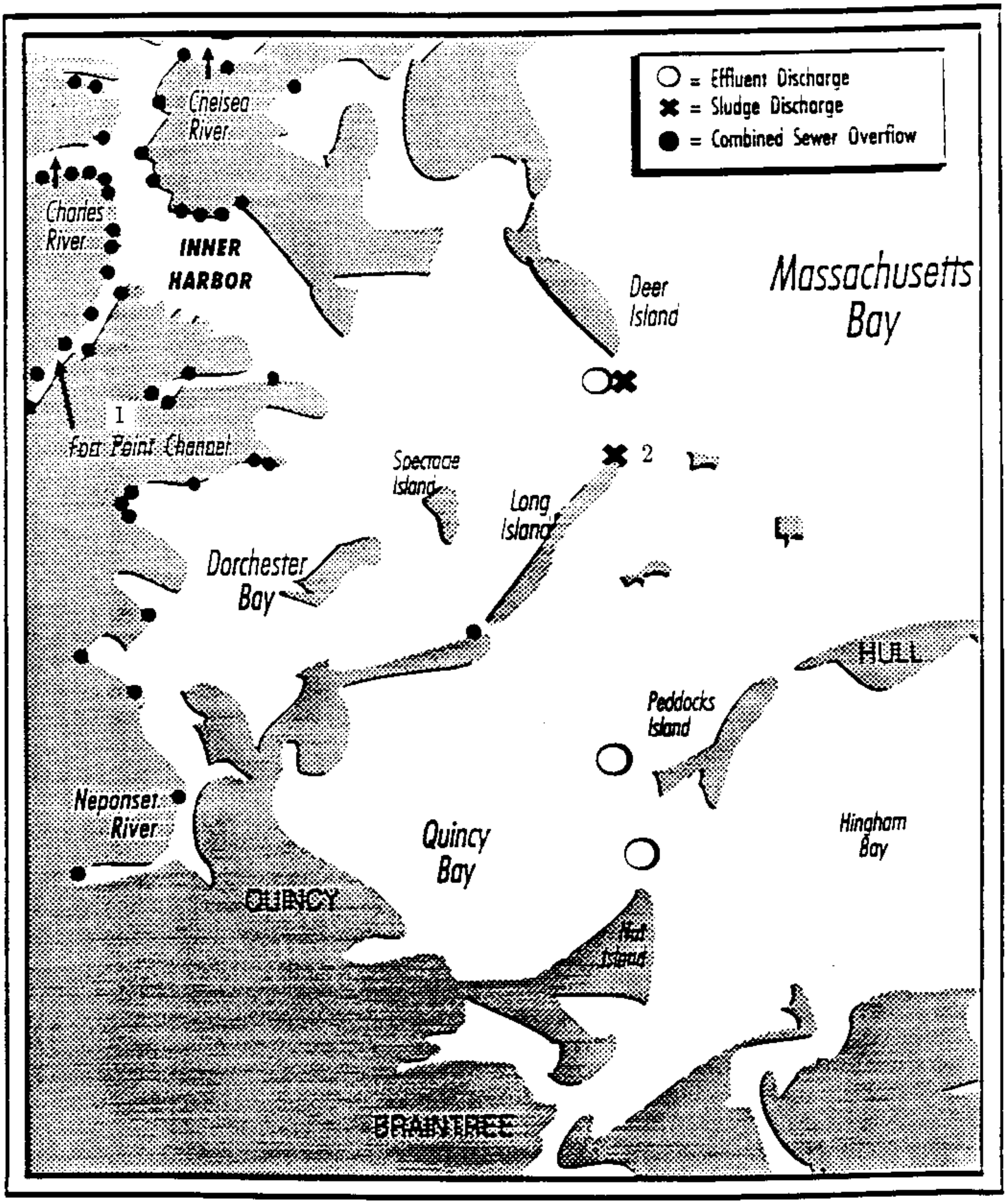

Figure 1. Locations of Fort Point Channel (1) and Nut Island sludge (2) tracer studies

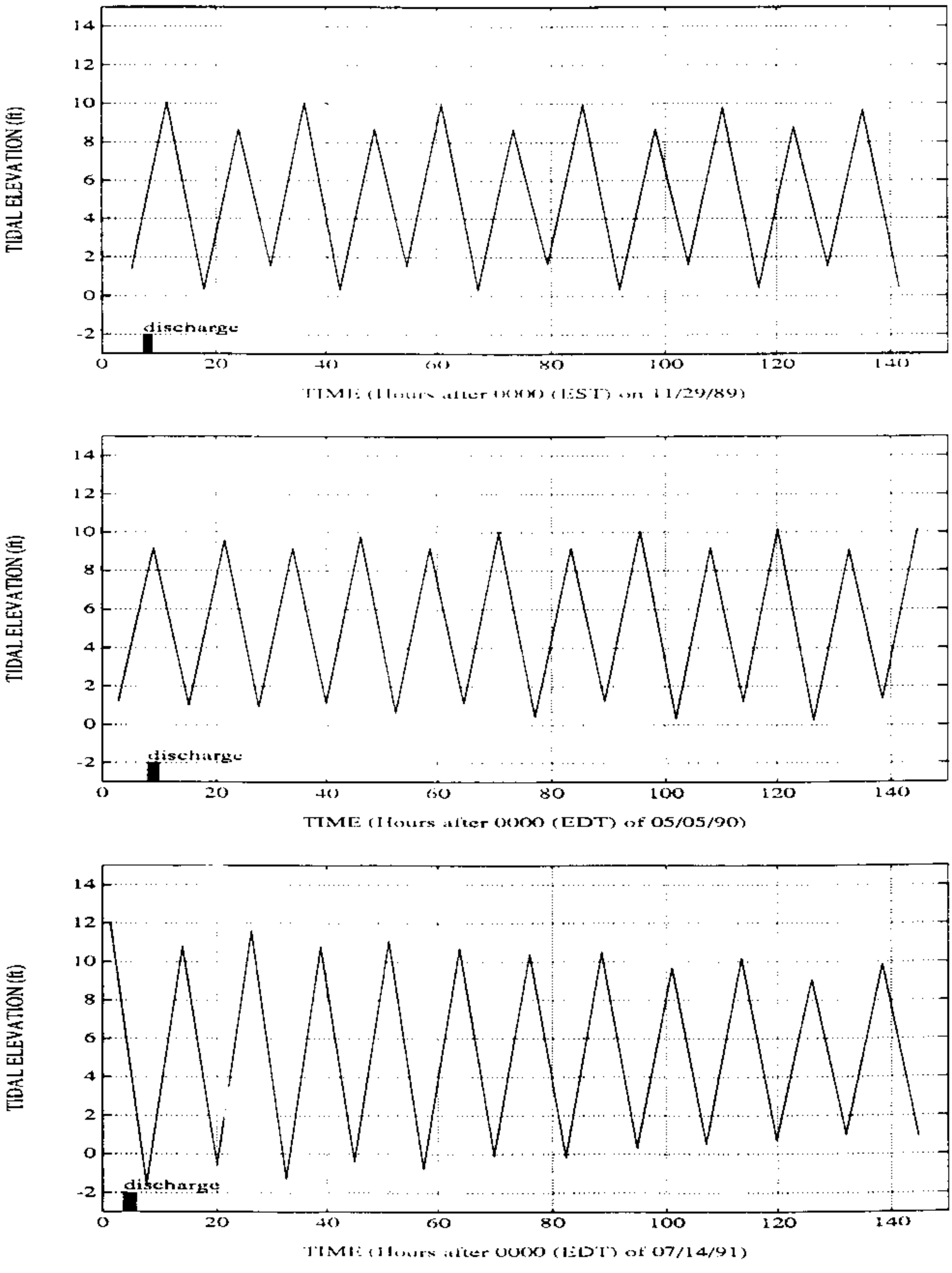

Figure 2. Tidal elevation versus time for three studies (linear interpolation between successive high and low waters; from NOAA Tide Tables)

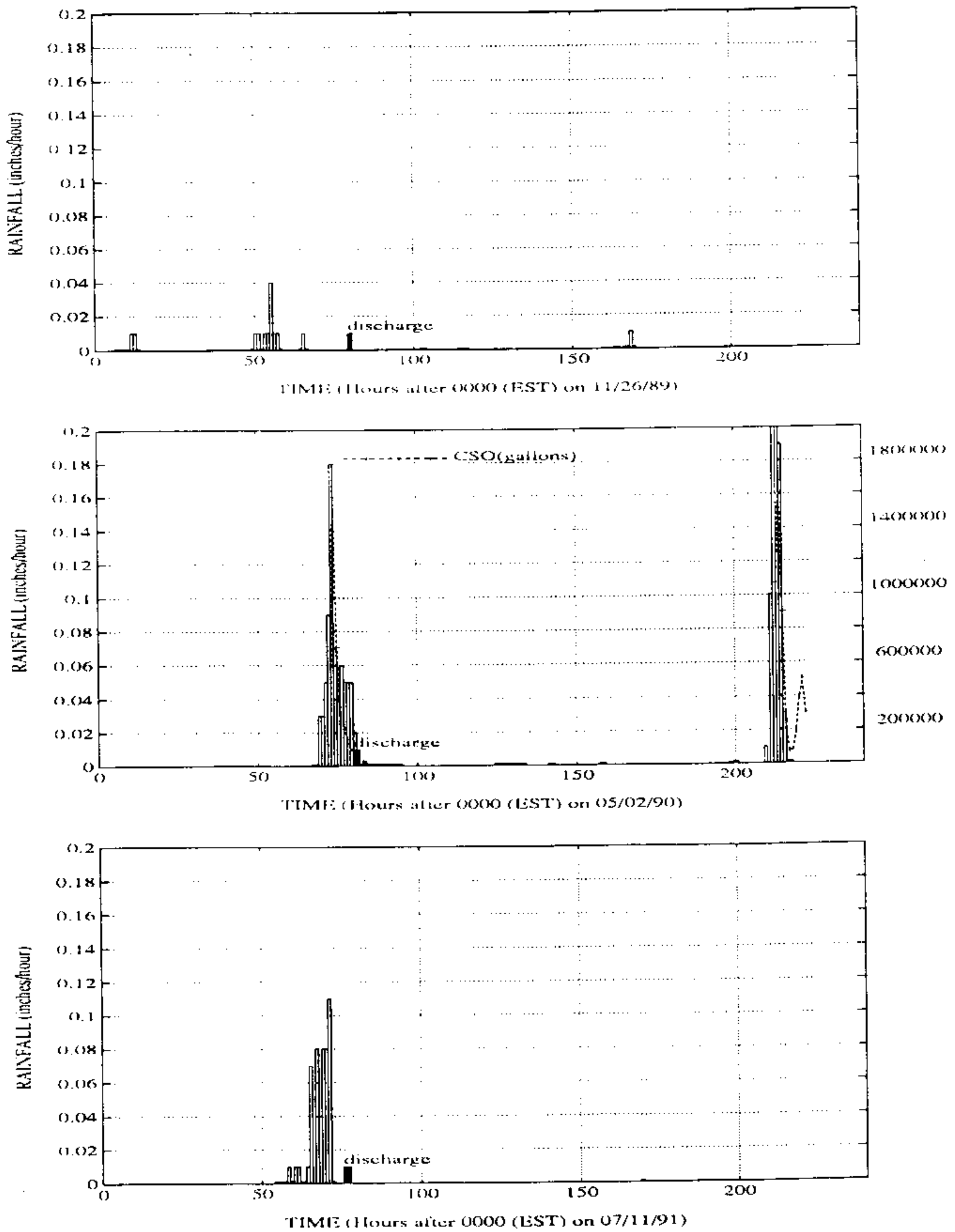

Figure 3. Rainfall versus time for three studies: a) November/December 1989, b) May 1990, and c) July 1991. Dashed line in middle study is predicted CSO flow rate from CDM model (right axis).

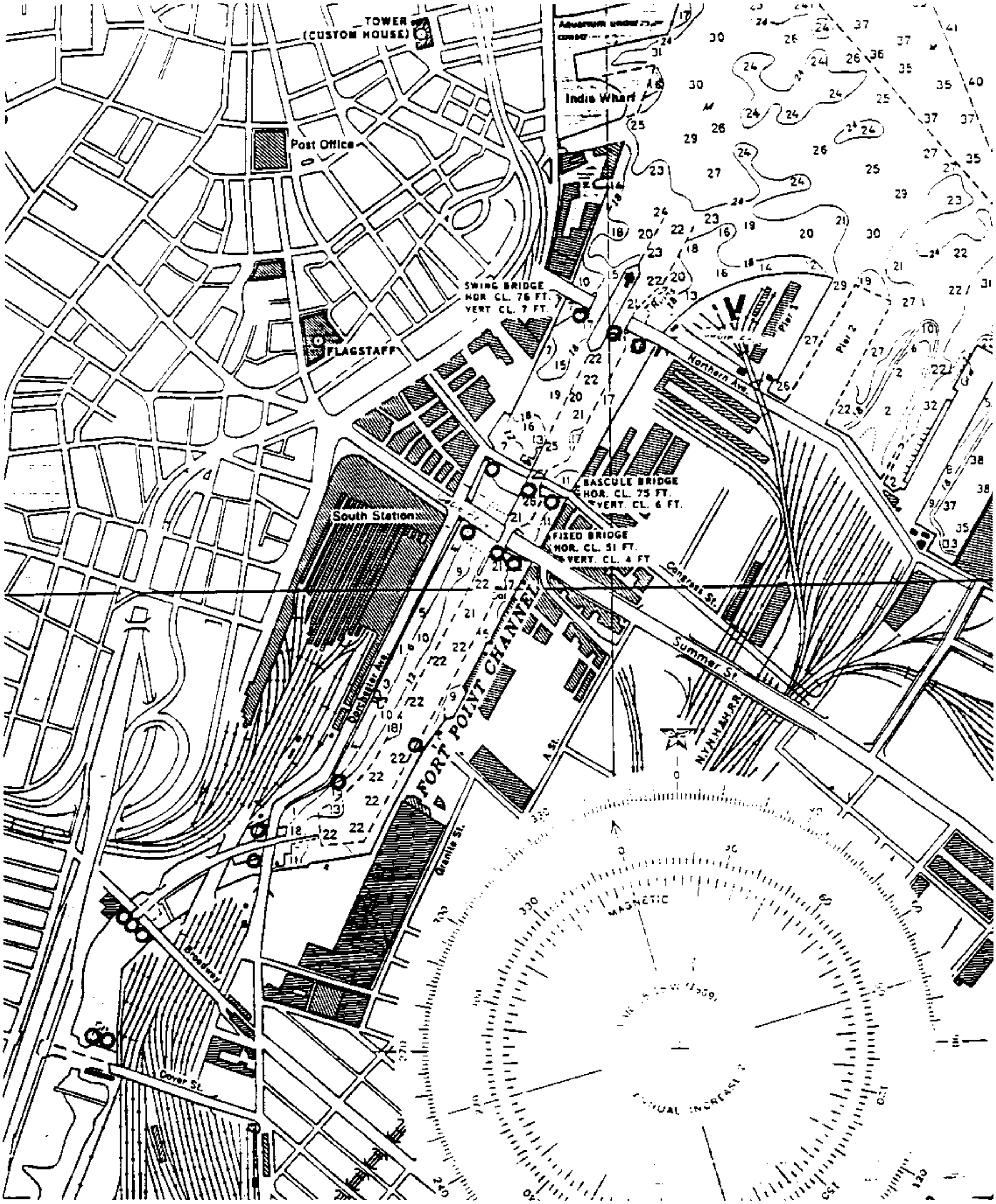

Figure 4. Plan view of Fort Point Channel showing typical sampling locations. Tracers were discharged to head of the channel at BOS070 culvert in SW corner.

DYE CONCENTRATION IN FORT POINT CHANNEL (11/30/89, AM)

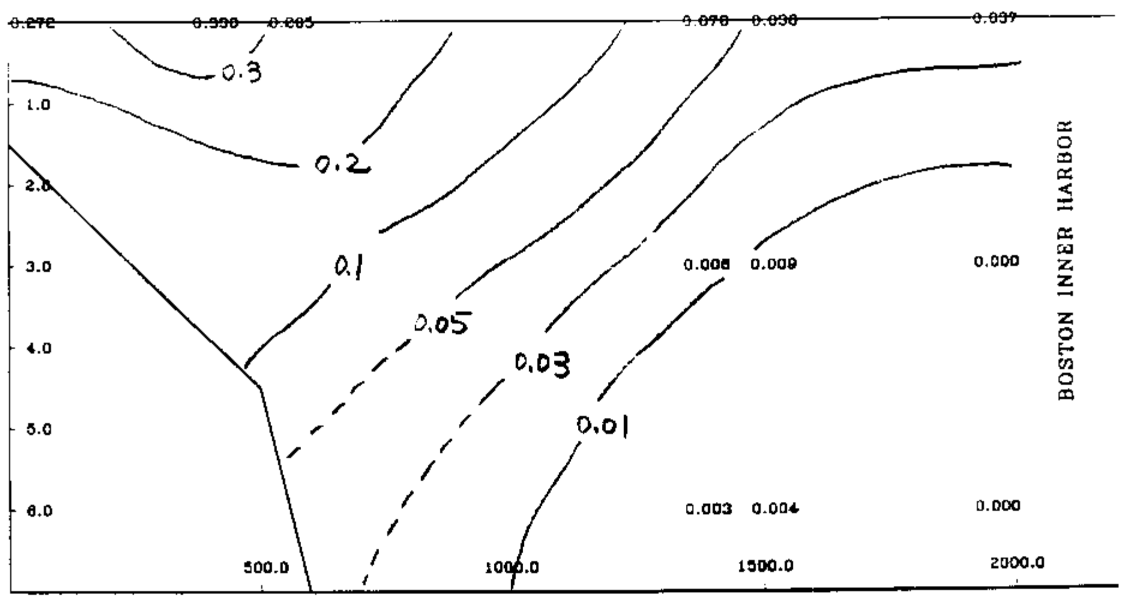

Figure 5. Typical longitudinal-vertical section of dye concentration measured during the first study

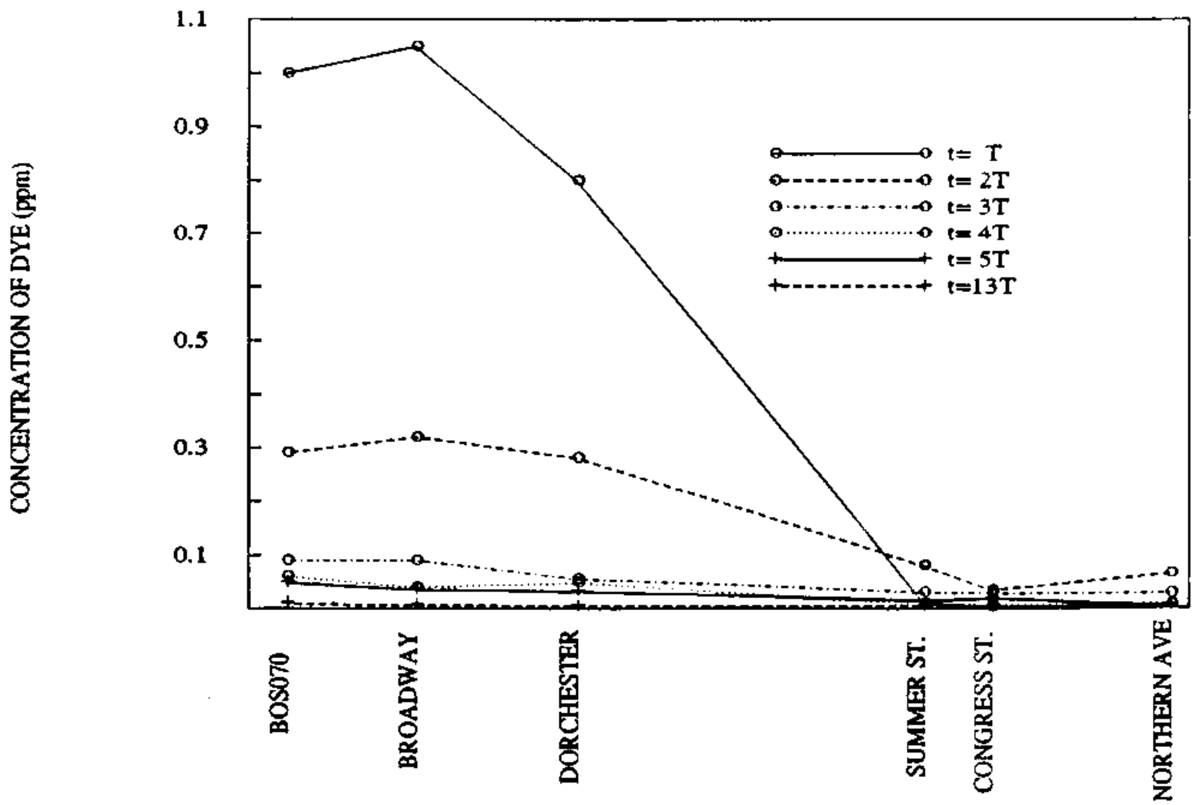

Figure 6. Dye concentration in FPC, Nov./Dec. 1989 study

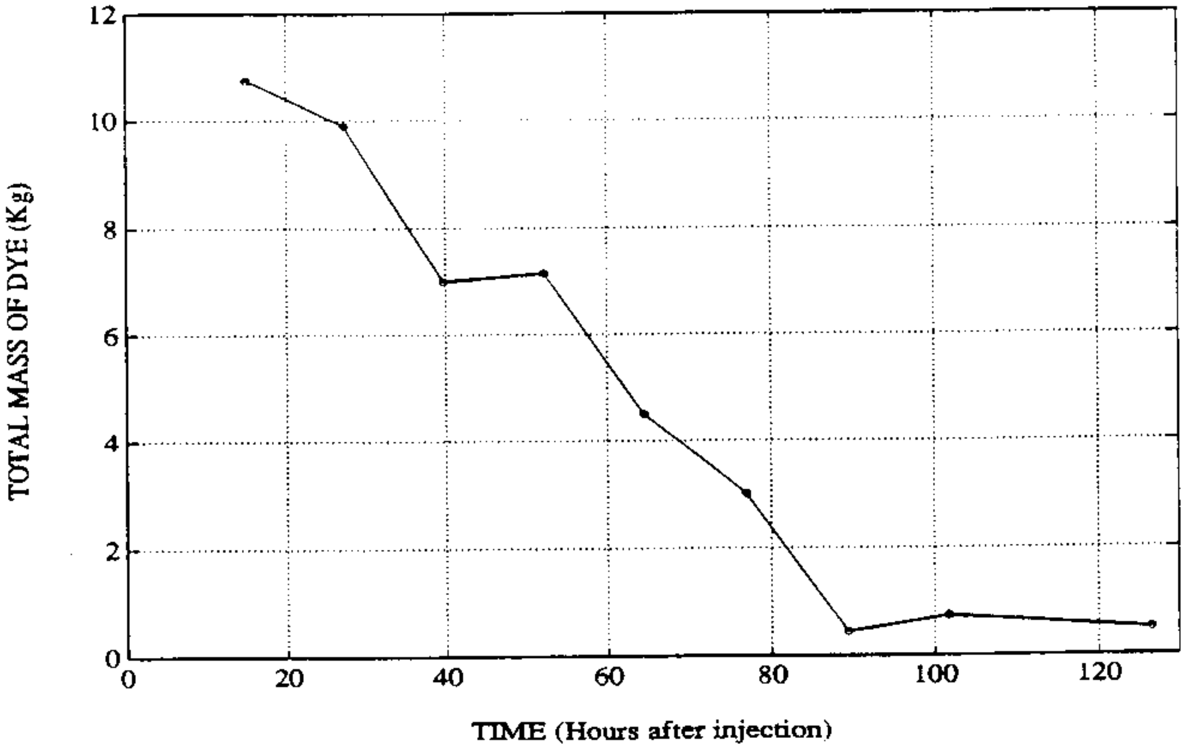

Figure 7. Dye mass vs. time, Nov./Dec. 1989 study

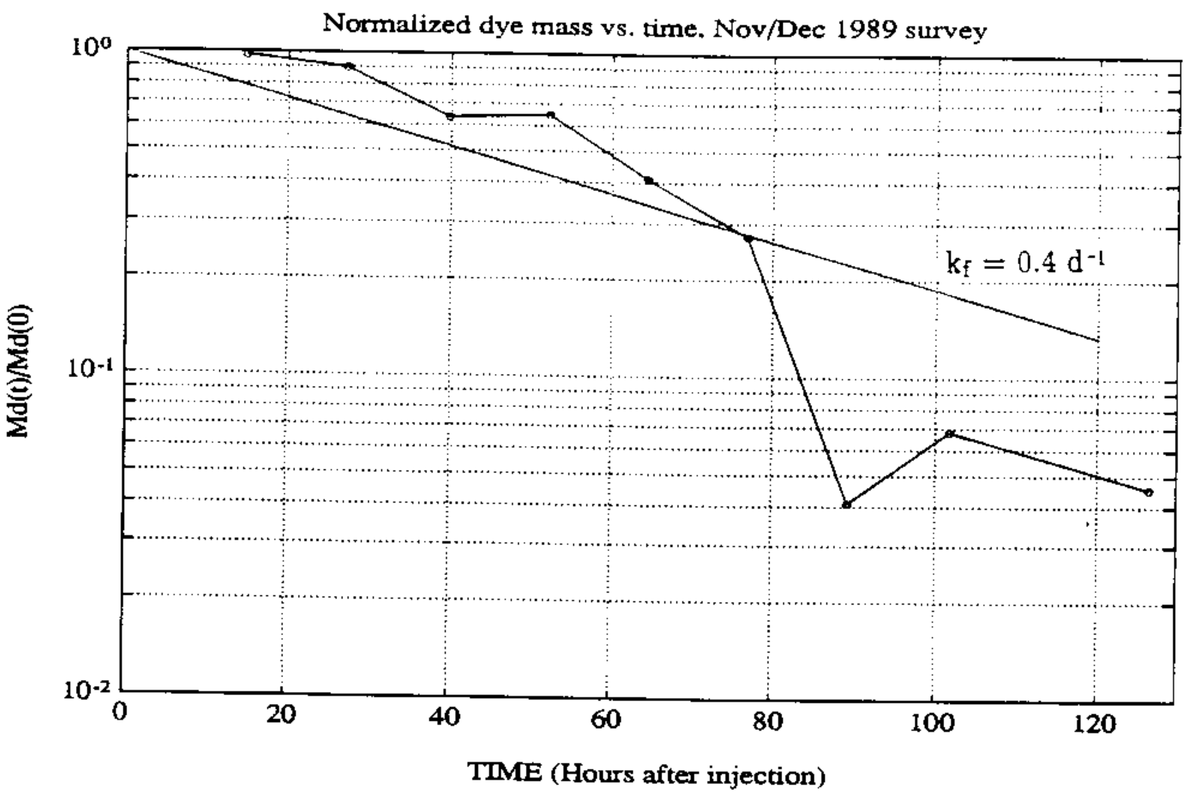

Figure 8. Normalized dye mass vs. time, Nov./Dec. 1989 study

SALINITY MEASUREMENTS IN FORT POINT CHANNEL (12/03/89, PM)

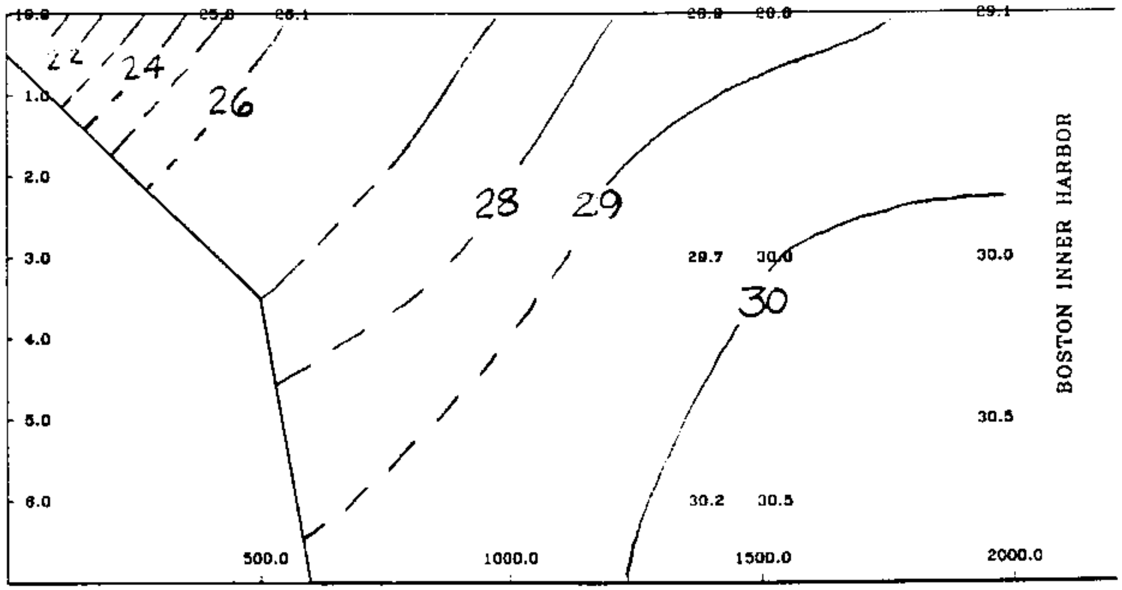

Figure 9. Typical longitudinal-vertical section of salinity measured during Nov./Dec. 1989 study

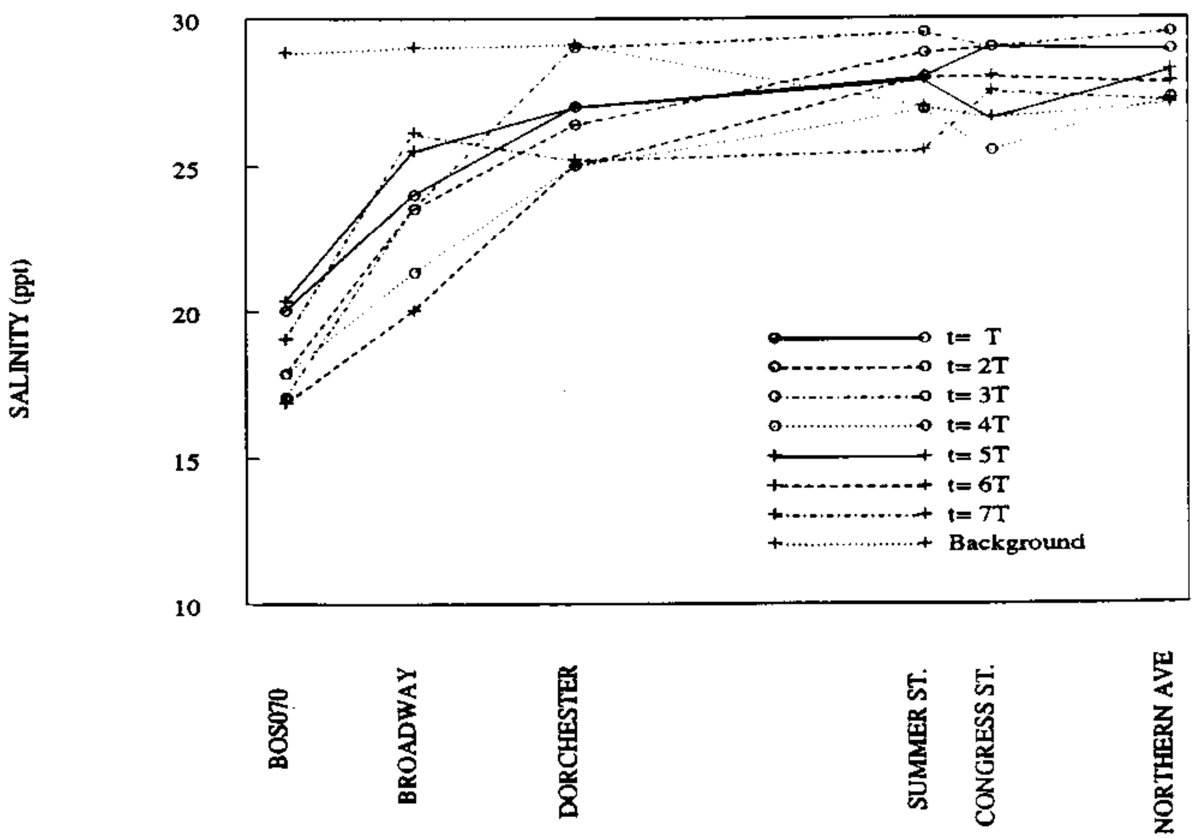

Figure 10. Surface salinity in FPC, Nov./Dec. 1989 study

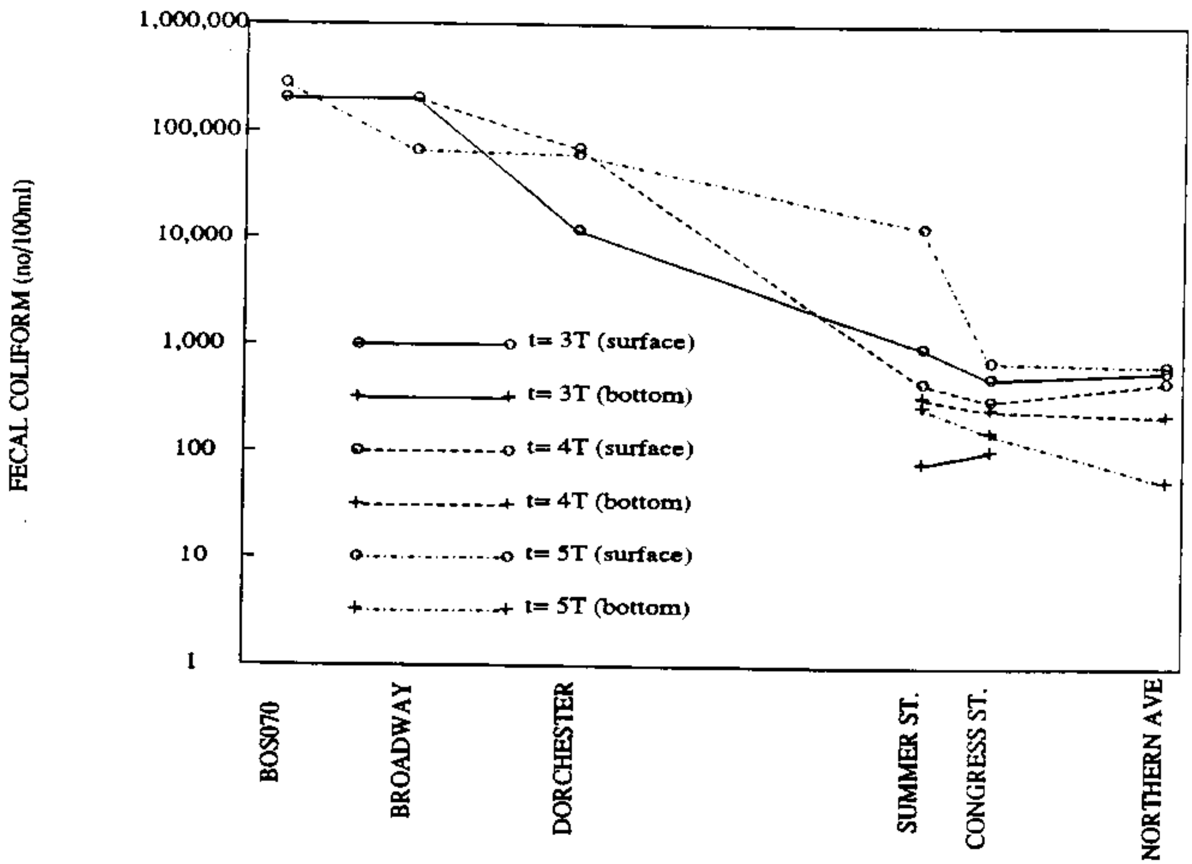

Figure 11. Fecal coliform in FPC, Nov. 30 and Dec. 1, 1989

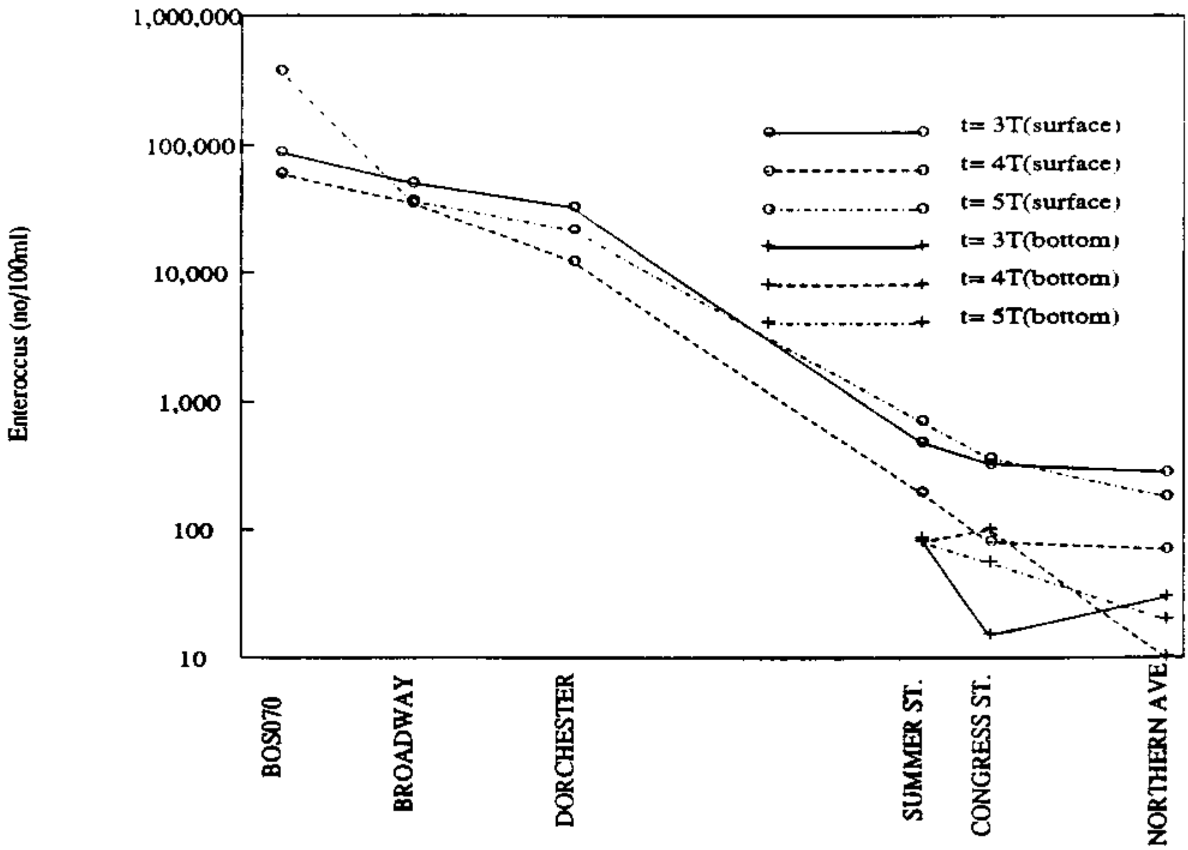

Figure 12. *Enterococcus* levels in FPC, Nov. 30 and Dec. 1, 1989

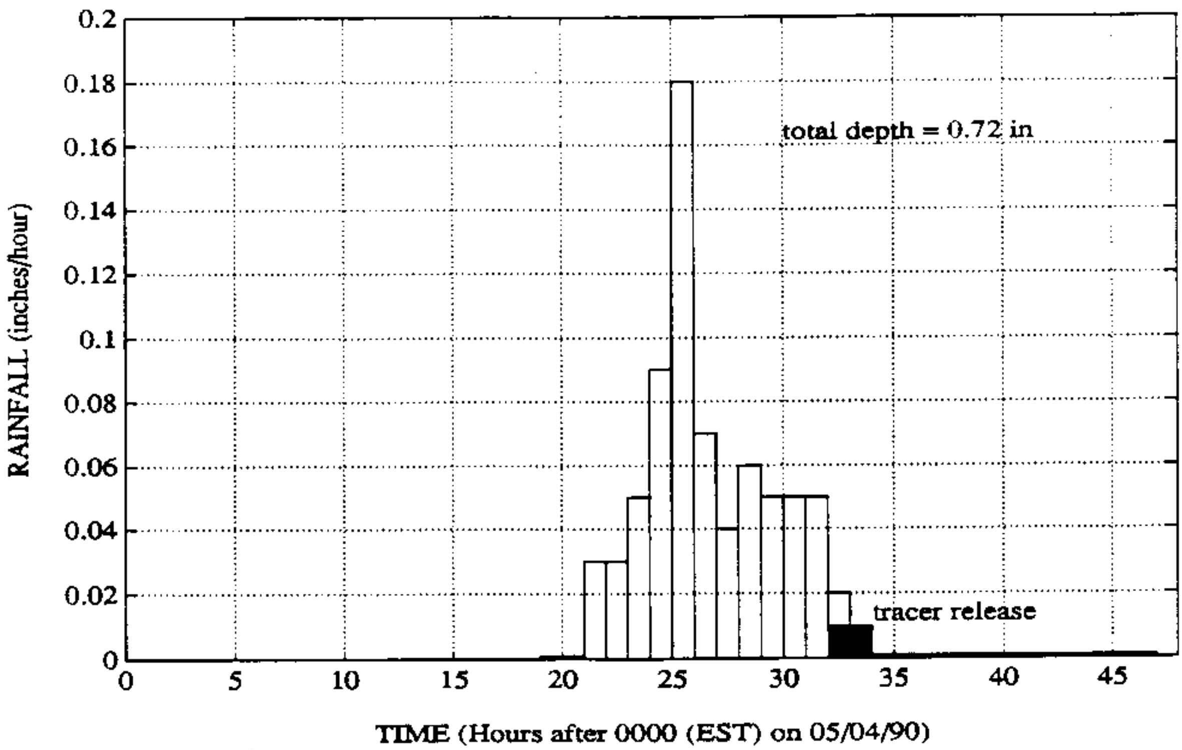

Figure 13. Rainfall at Logan Airport during May 1990 study

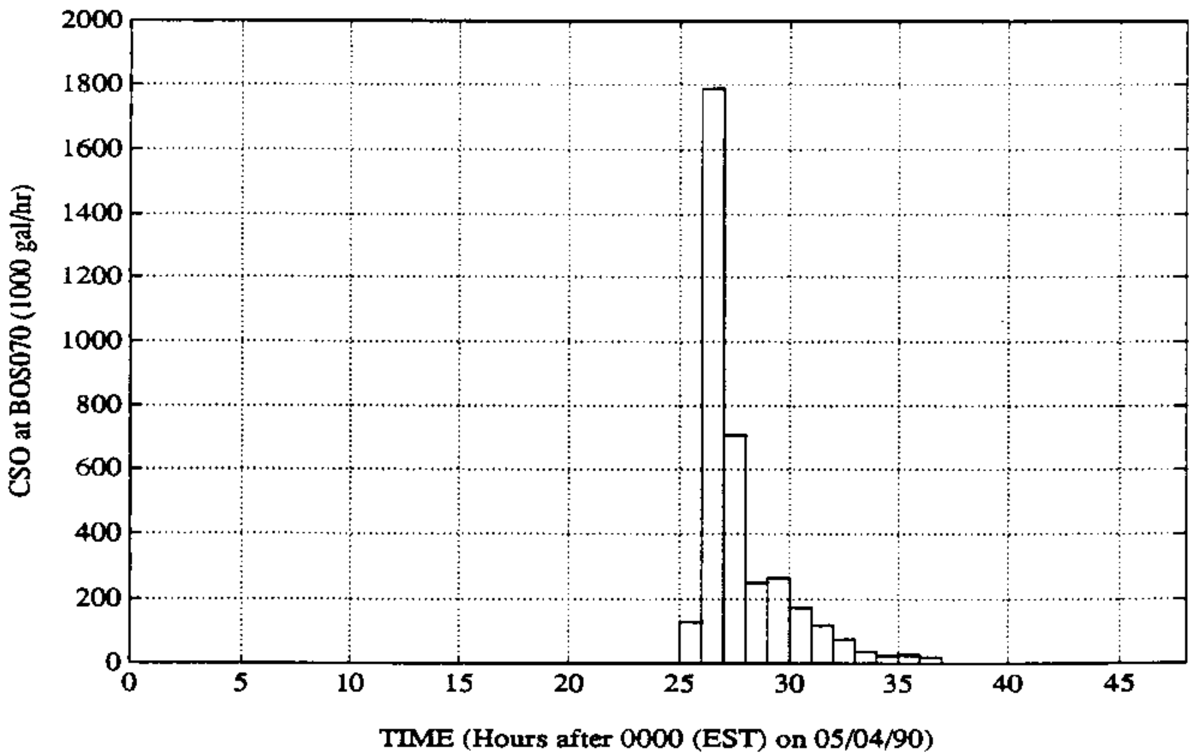

Figure 14. Predicted CSO discharge during May 1990 study

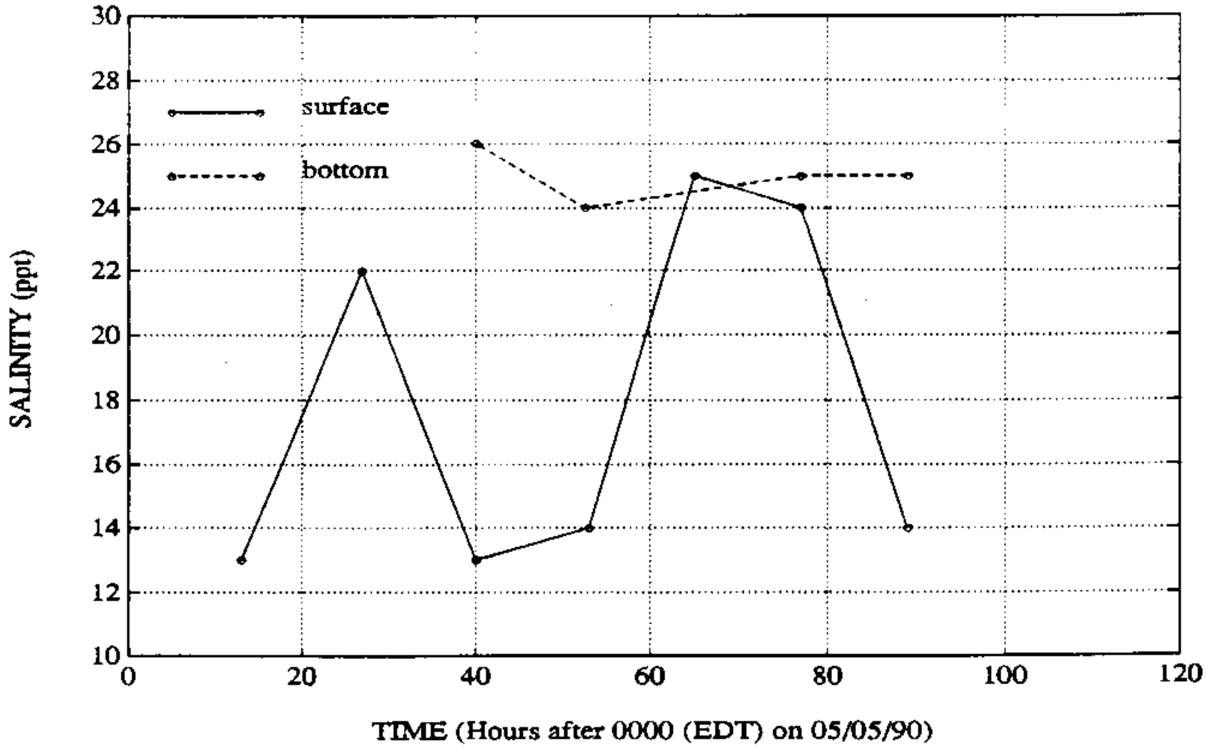

Figure 15. Salinity near outfall during May 1990 study

SALINITY MEASUREMENTS IN FORT POINT CHANNEL (05/05/90)

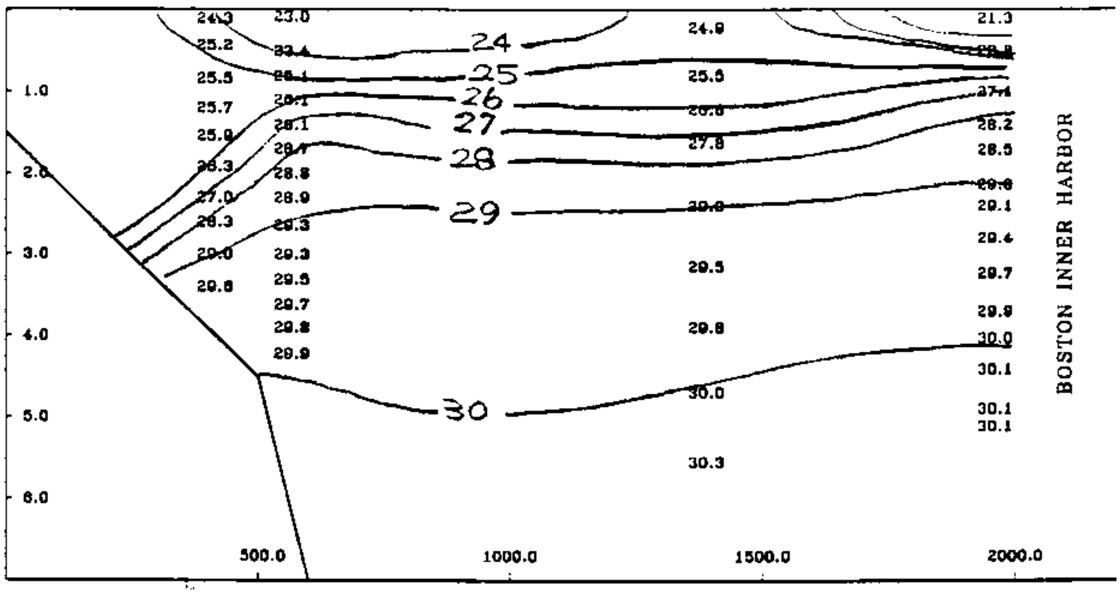

Figure 16. Typical longitudinal-vertical sections of salinity measured during the second study (UMass/B data) on three dates: a) May 5, 1990

SALINITY MEASUREMENTS IN FORT POINT CHANNEL (05/06/90)

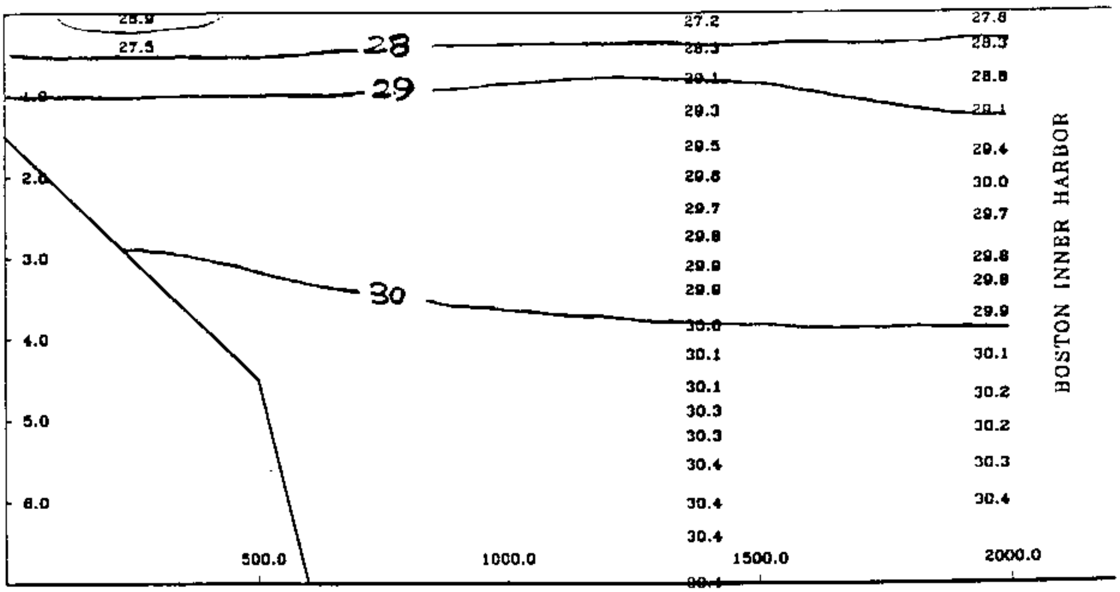

Figure 16. b) May 6, 1990

SALINITY MEASUREMENTS IN FORT POINT CHANNEL (05/07/90)

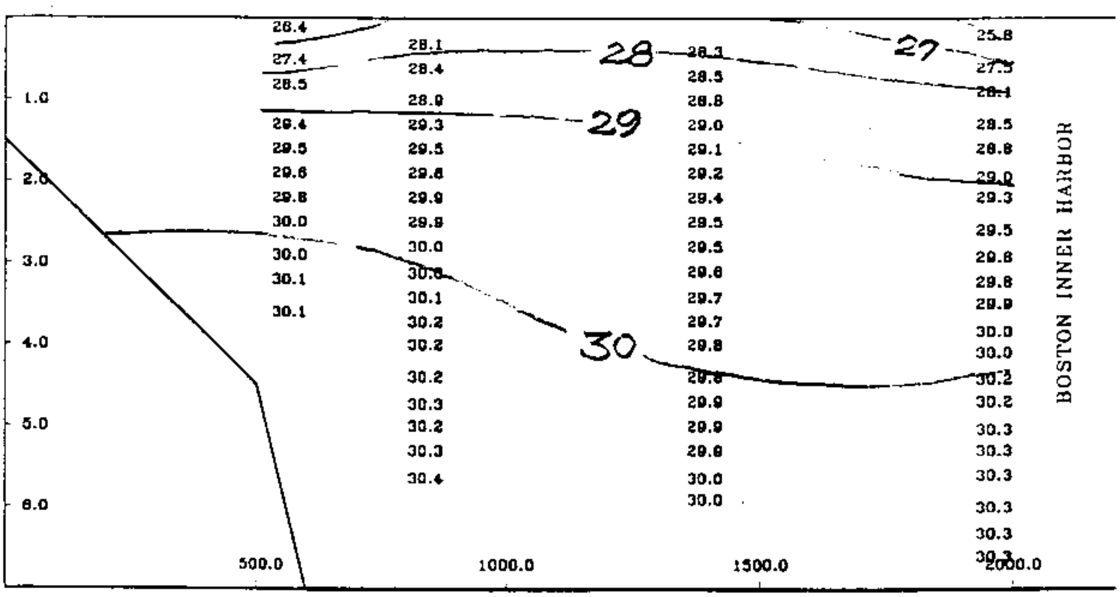

Figure 16. c) May 7, 1990

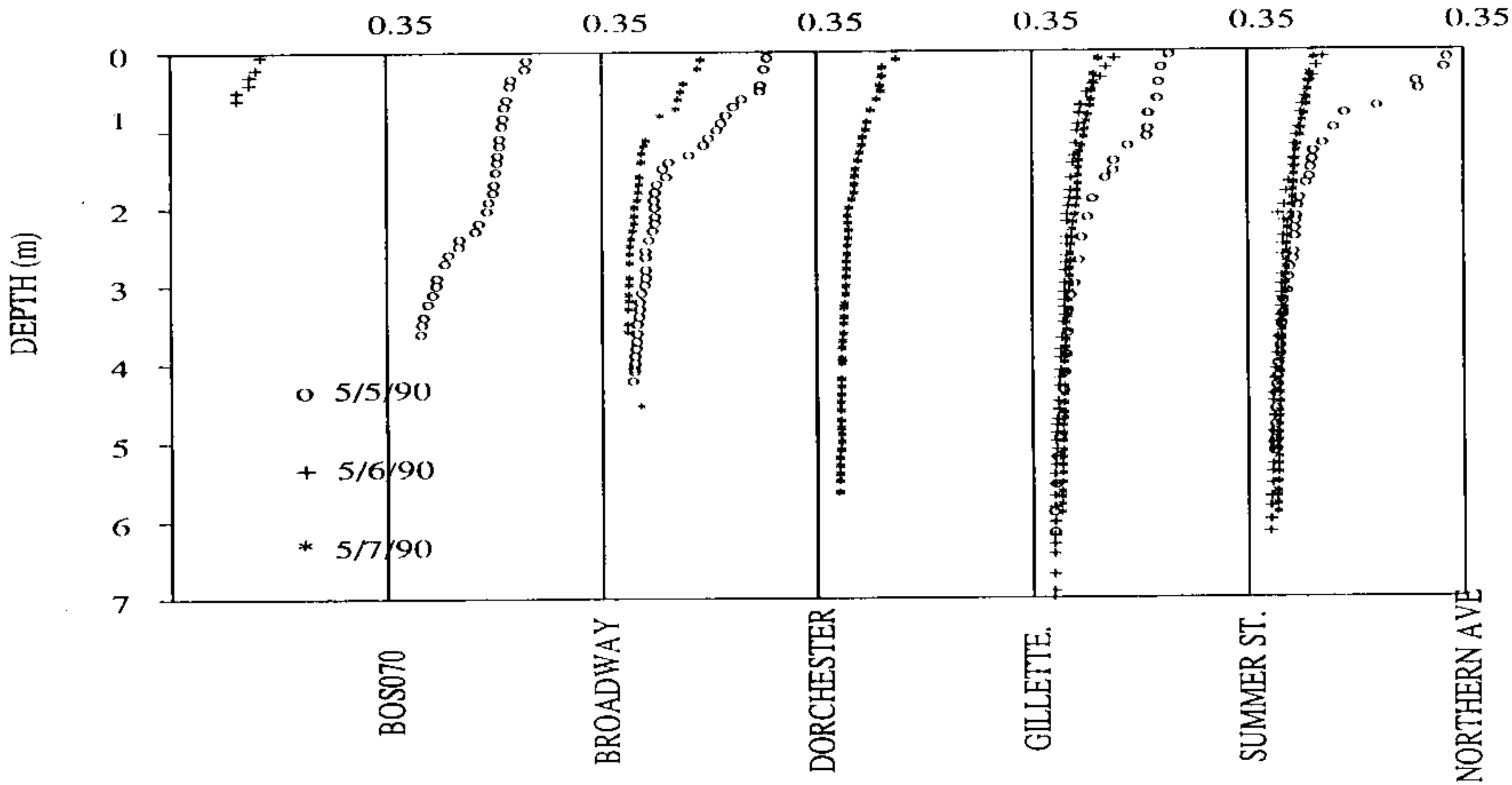

Figure 17. Freshness in FPC, May 1990

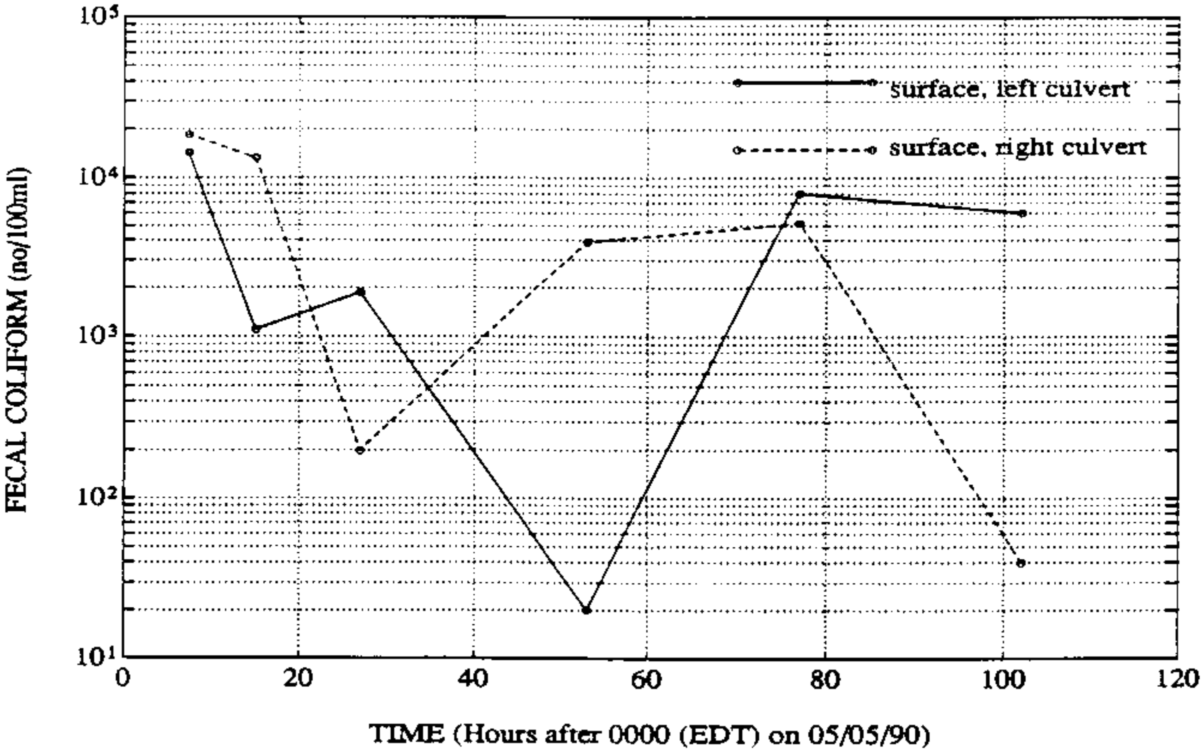

Figure 18. Fecal coliform near outfall during May 1990 study

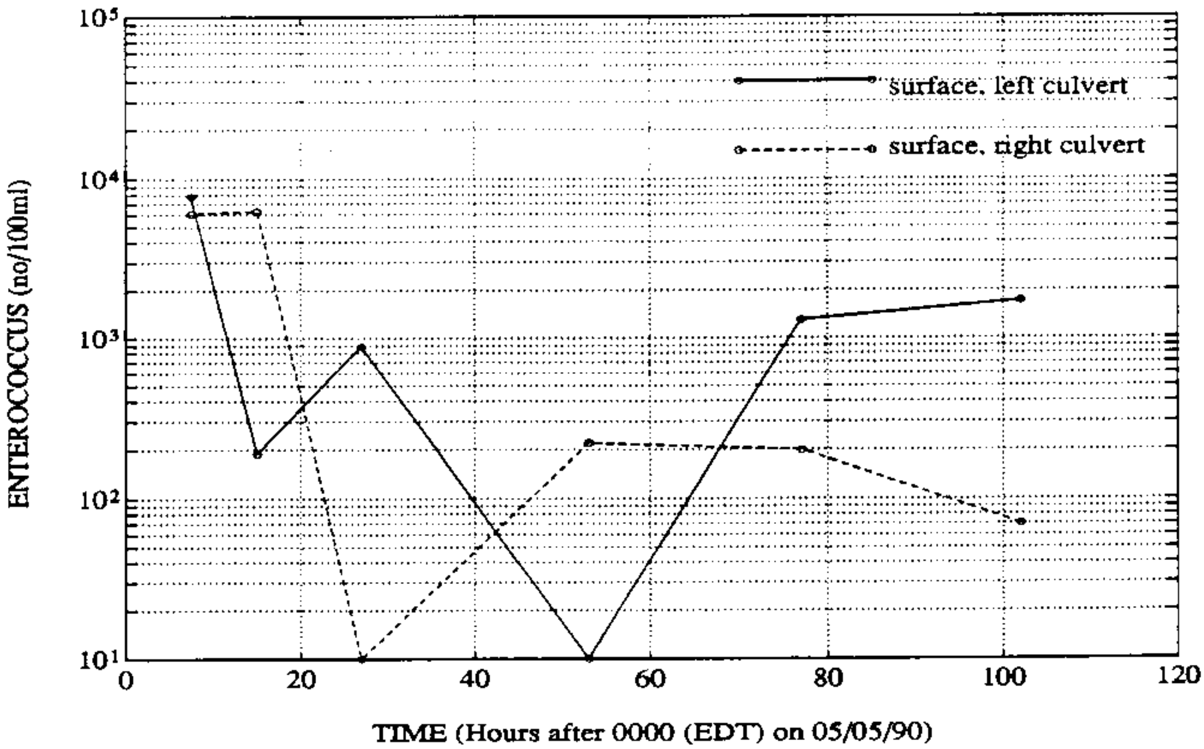

Figure 19. *Enterococcus* near outfall during May 1990 study

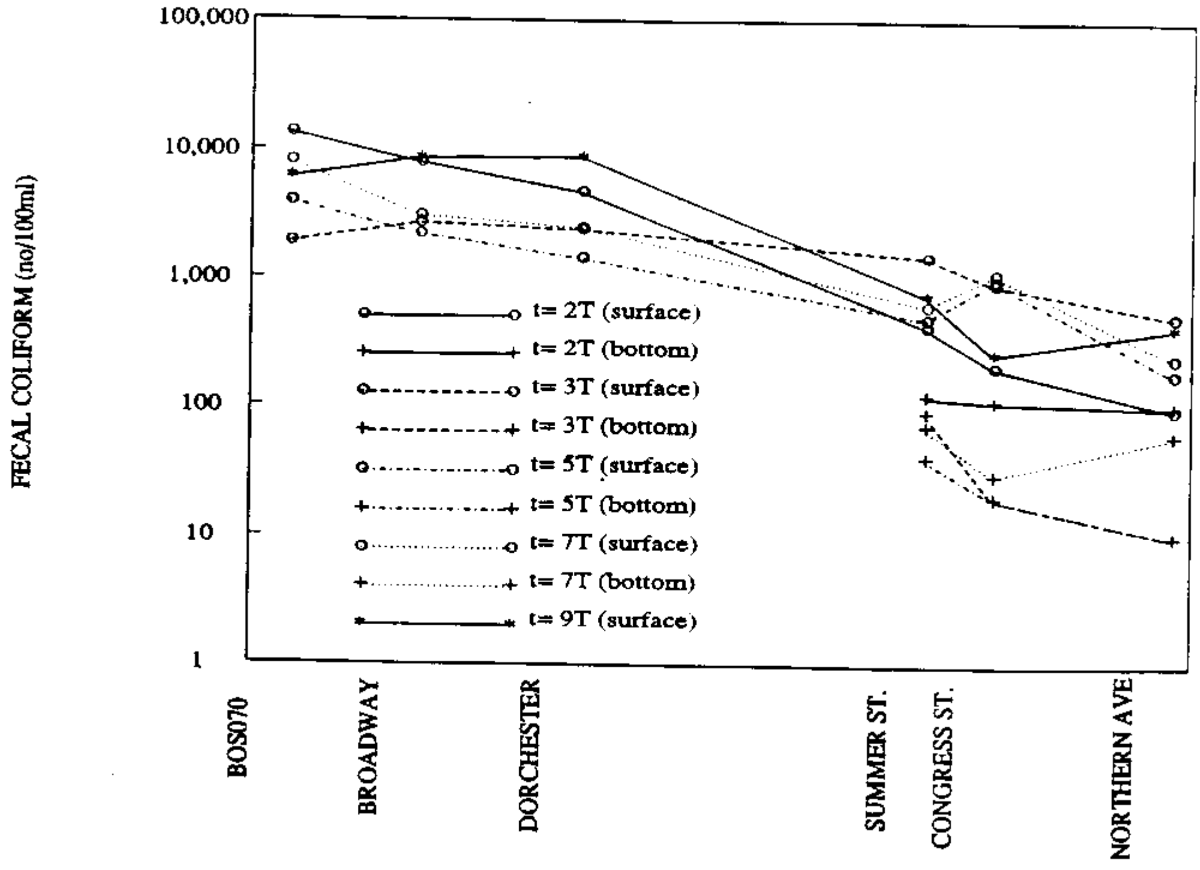

Figure 20. Fecal coliform levels in FPC, May 1990

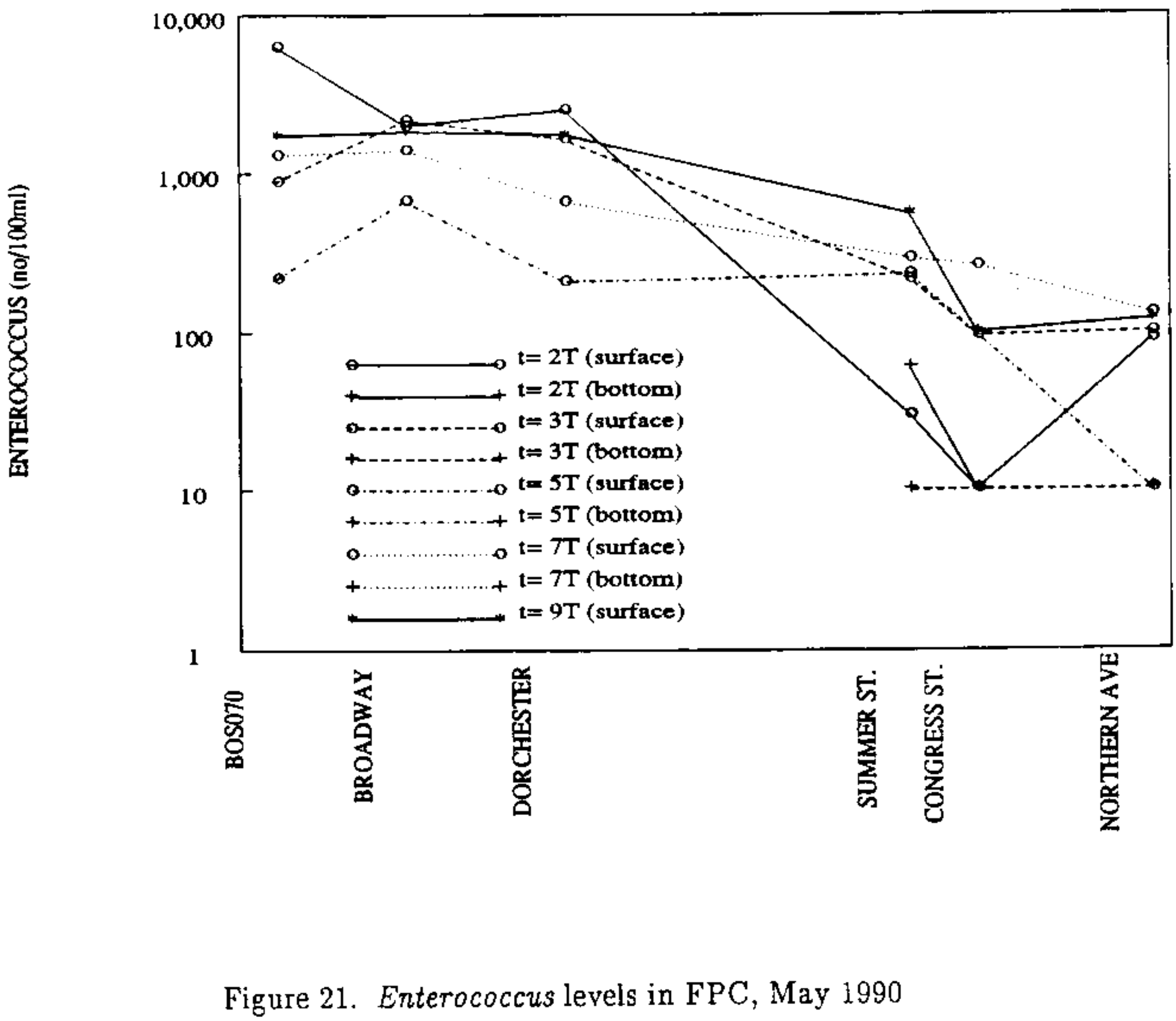

Figure 21. *Enterococcus* levels in FPC, May 1990

DYE CONCENTRATION IN FORT POINT CHANNEL (05/06/90, AM)

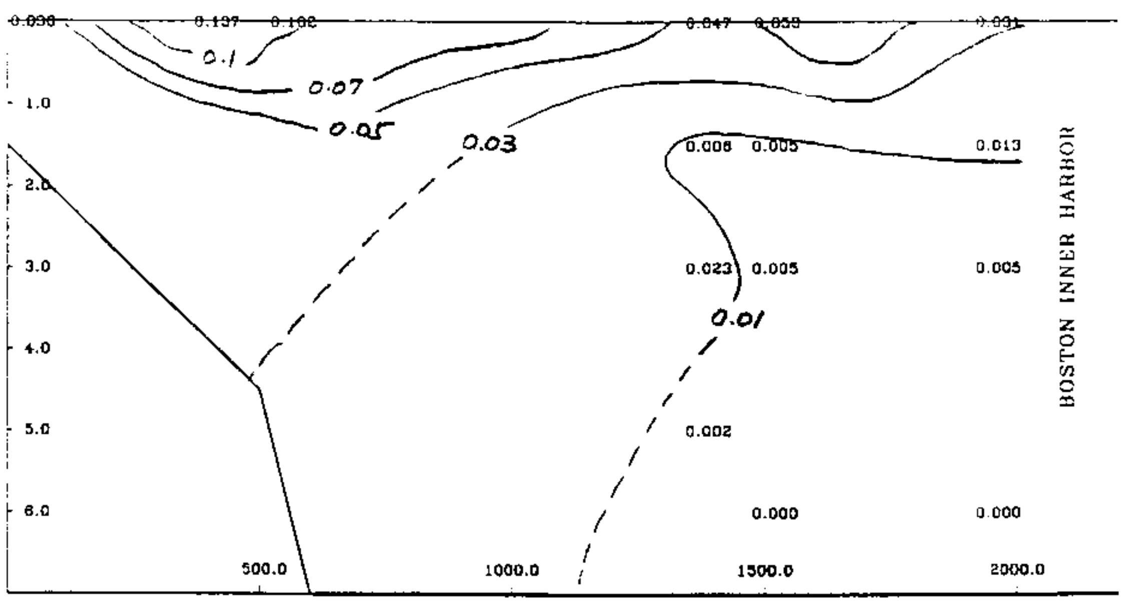

Figure 22. Typical longitudinal-vertical sections of dye concentration measured during the second study

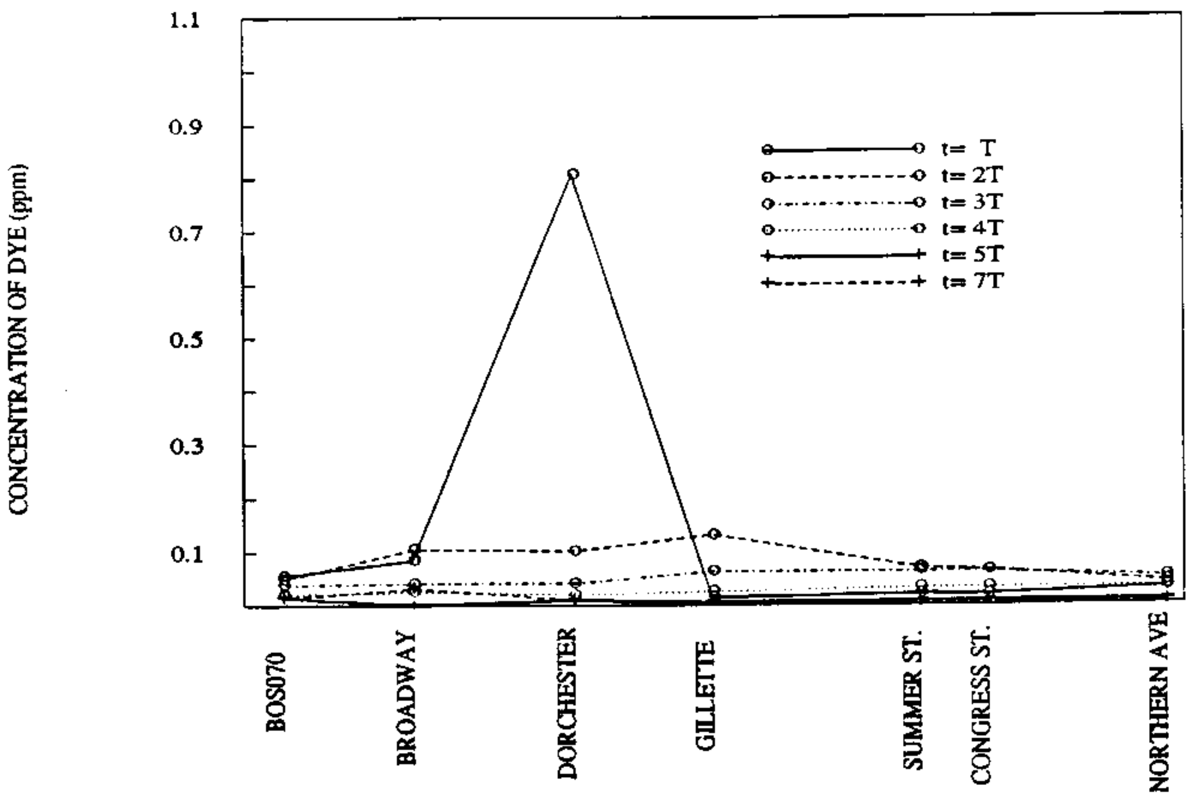

Figure 23. Dye concentration in FPC, May 1990

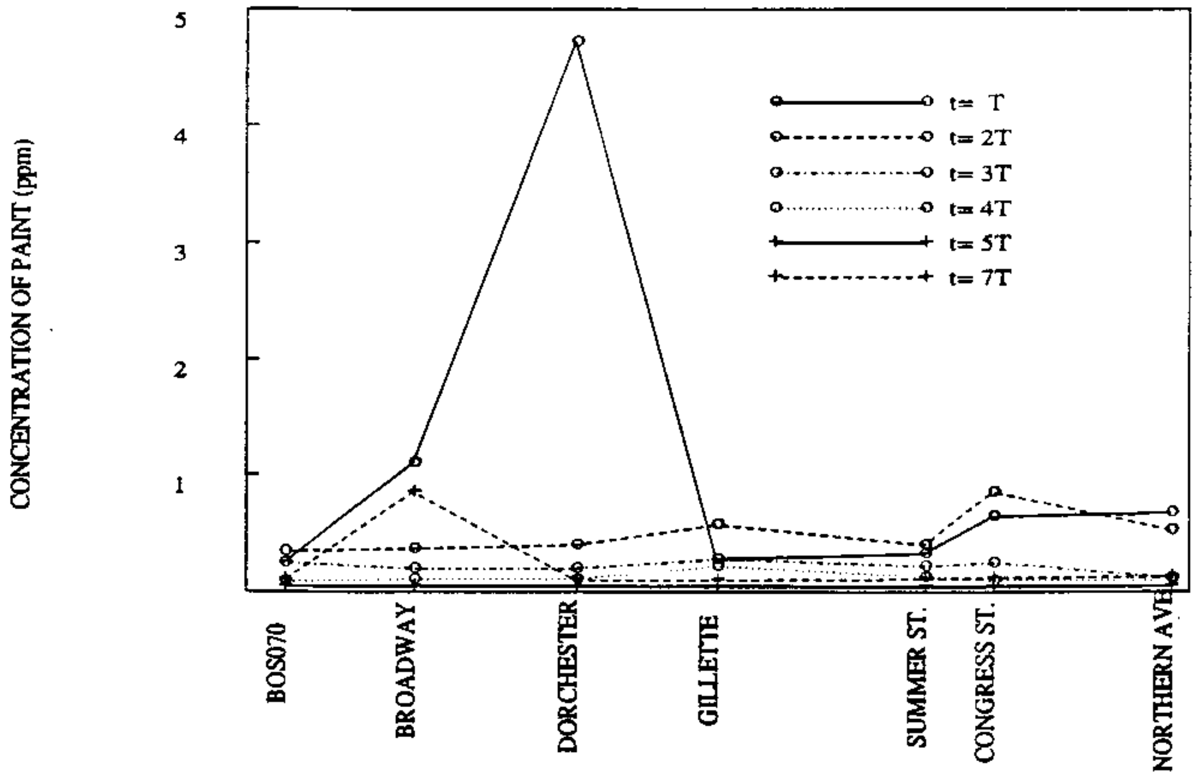

Figure 24. Paint concentration in FPC, May 1990

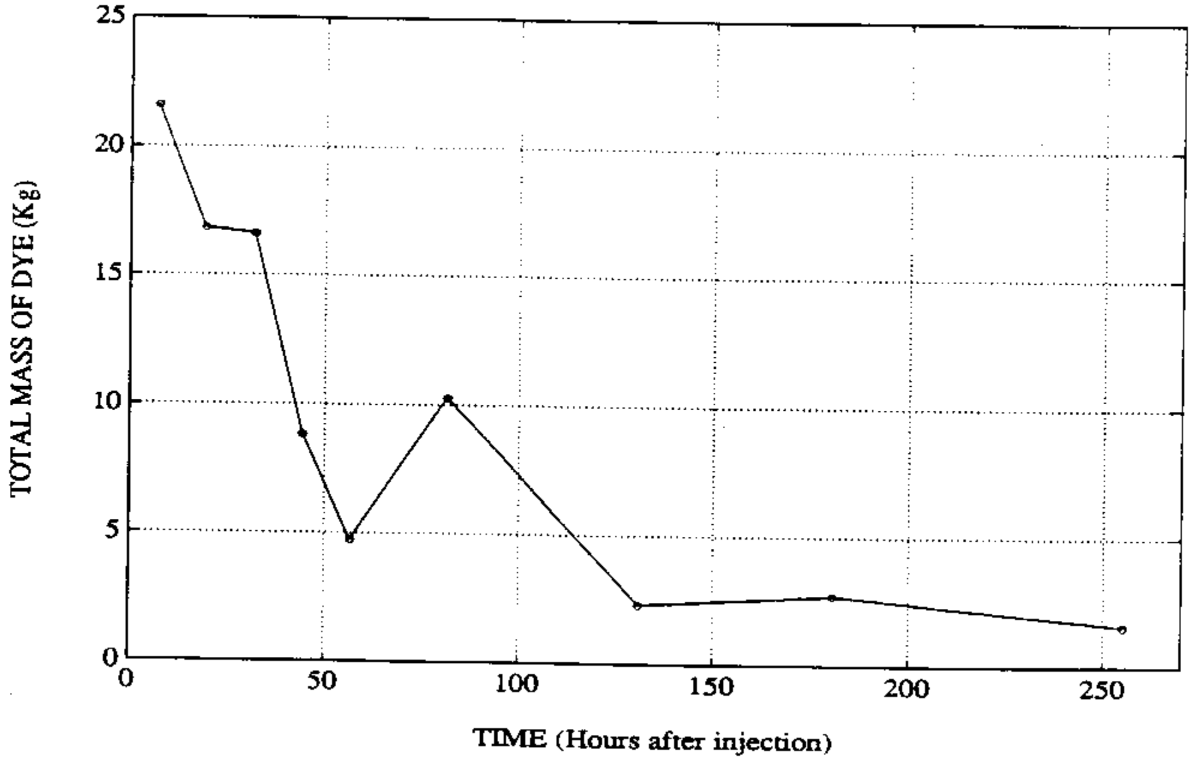

Figure 25. Dye mass vs. time, May 1990

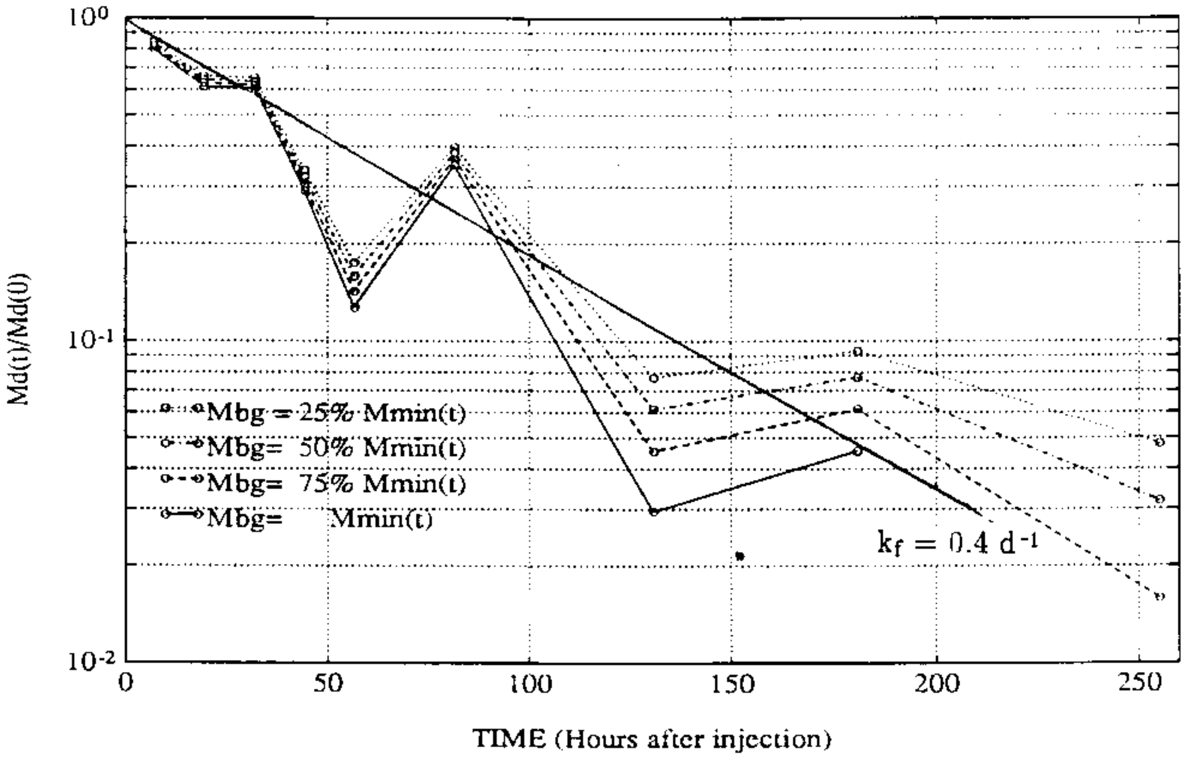

Figure 26. Normalized dye mass vs. time, May 1990. Different curves reflect different assumptions on background dye concentration.

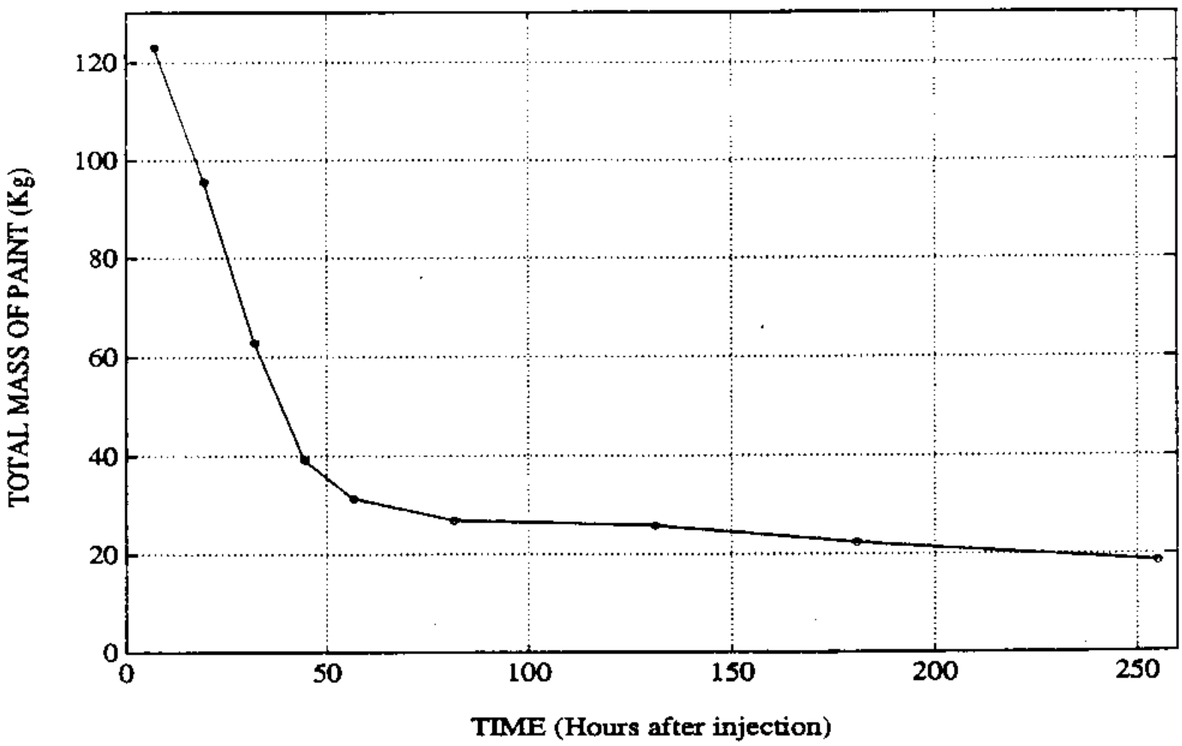

Figure 27. Paint mass vs. time, May 1990

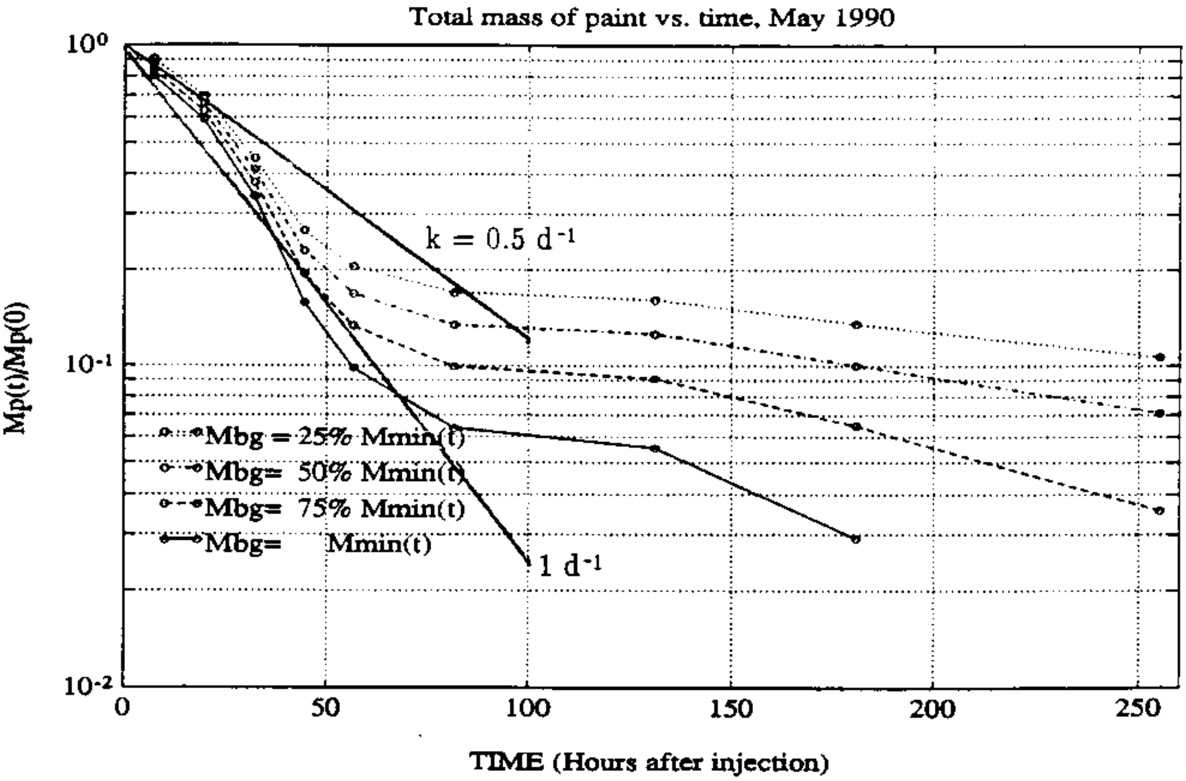

Figure 28. Total mass of paint vs. time, May 1990. Different curves reflect differ-
assumptions on background paint concentration.

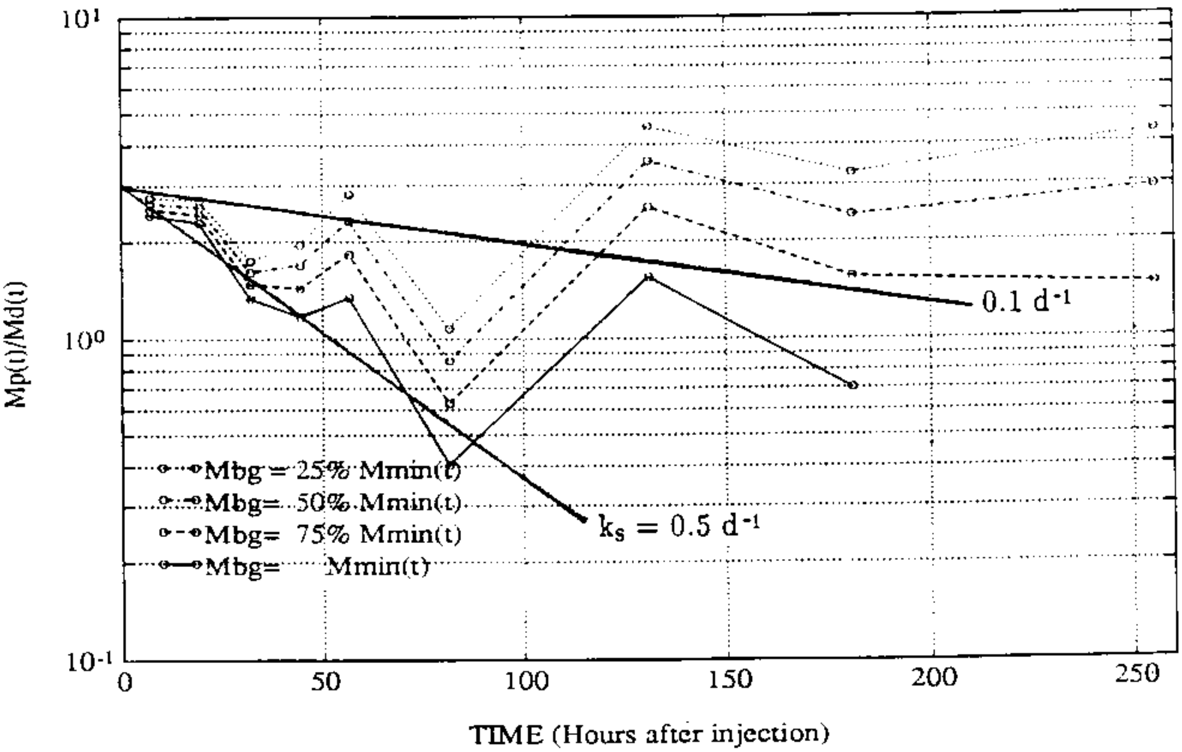

Figure 29. Ratio of paint mass to dye mass vs. time, May 1990. Different curves reflect different assumptions on background paint concentration.

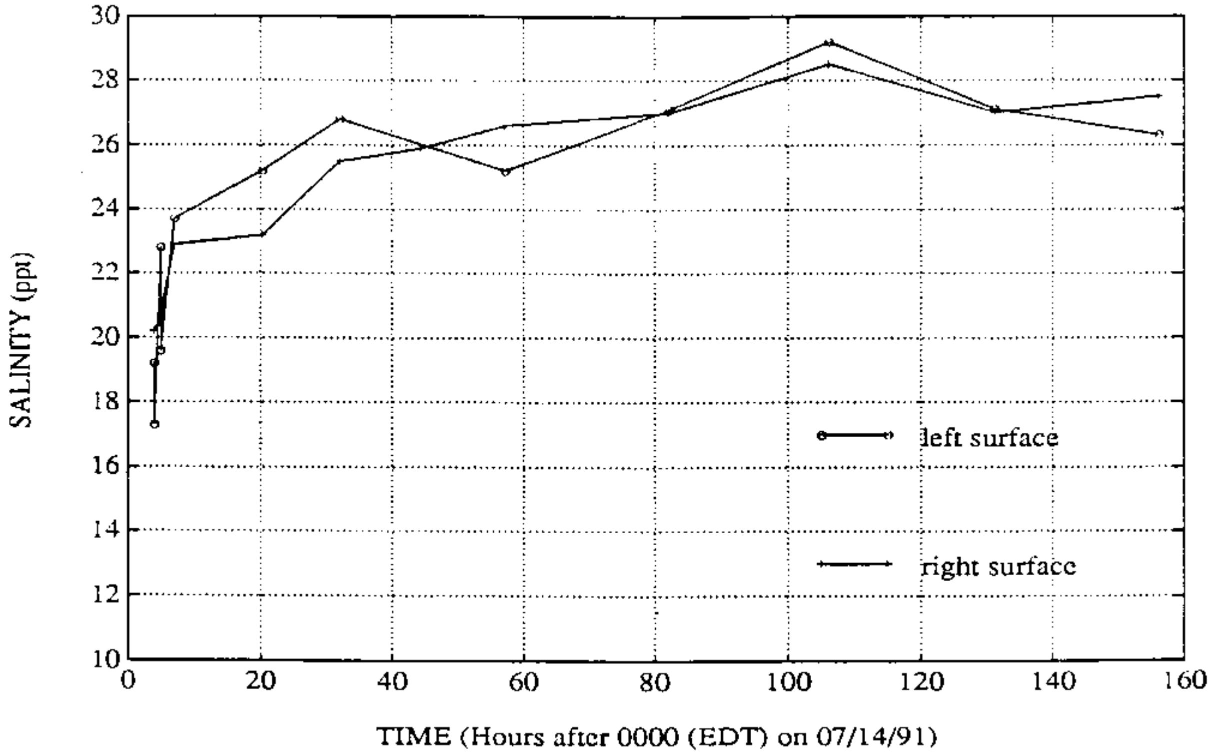

Figure 30. Salinity near outfall during July 1990 study

SALINITY MEASUREMENTS IN FORT POINT CHANNEL (07/14/91, PM)

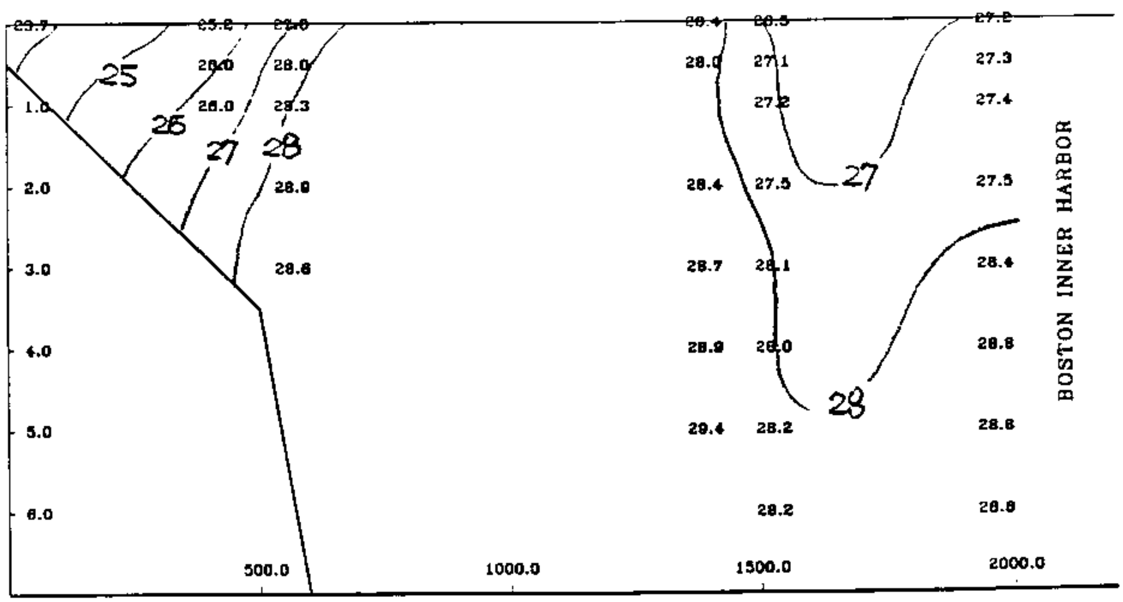

Figure 31. Typical longitudinal-vertical section of salinity measured during the third study

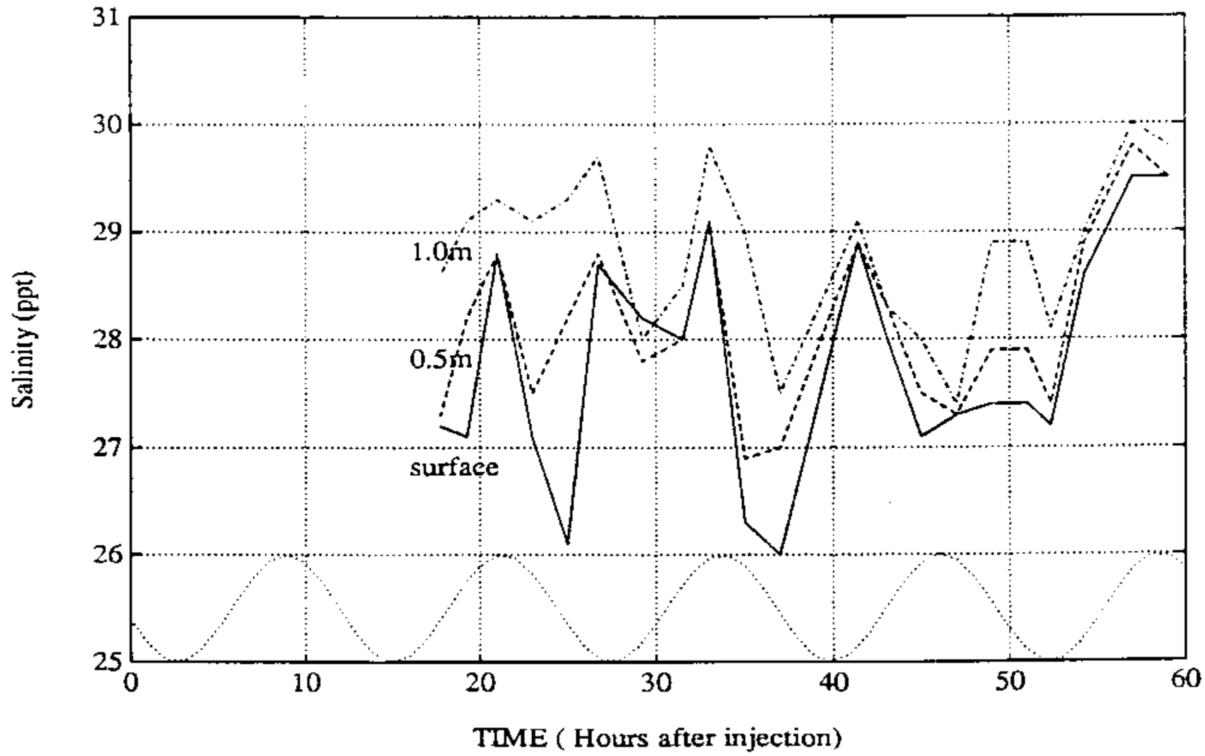

Figure 32. Salinity at Northern Avenue vs. time, July 1990

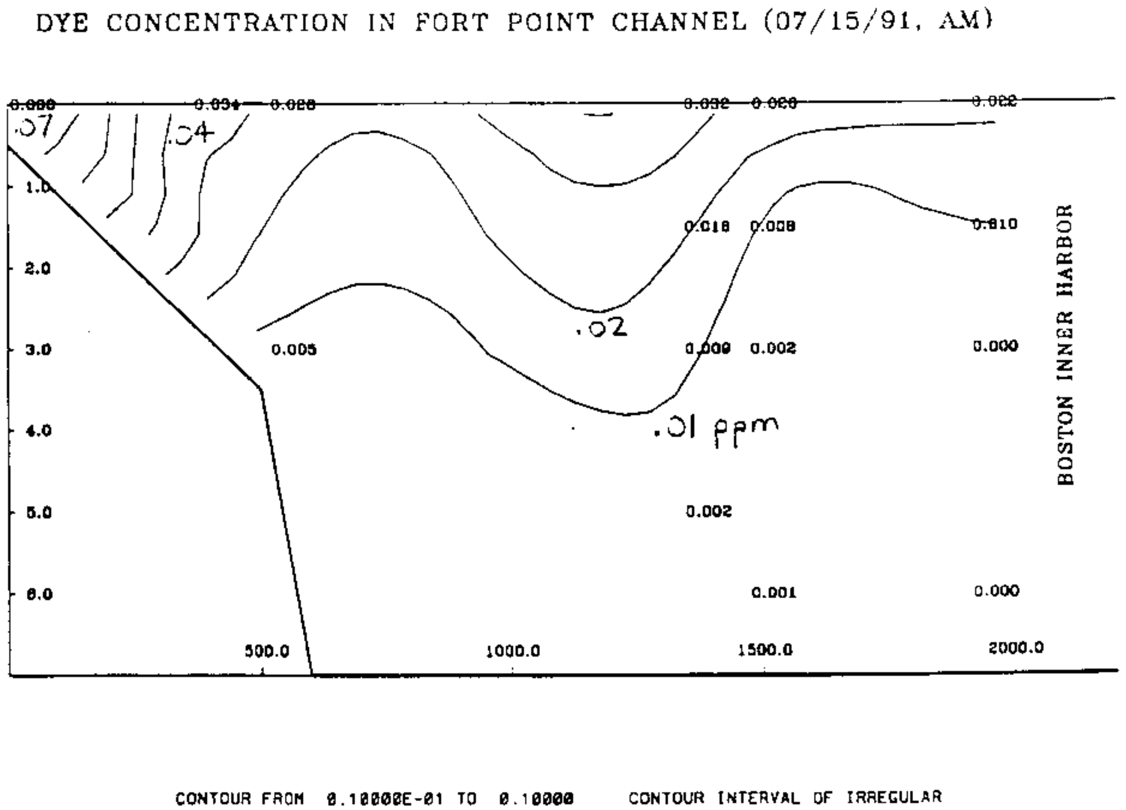

Figure 33. Typical longitudinal-vertical section of dye concentration measured during the third study

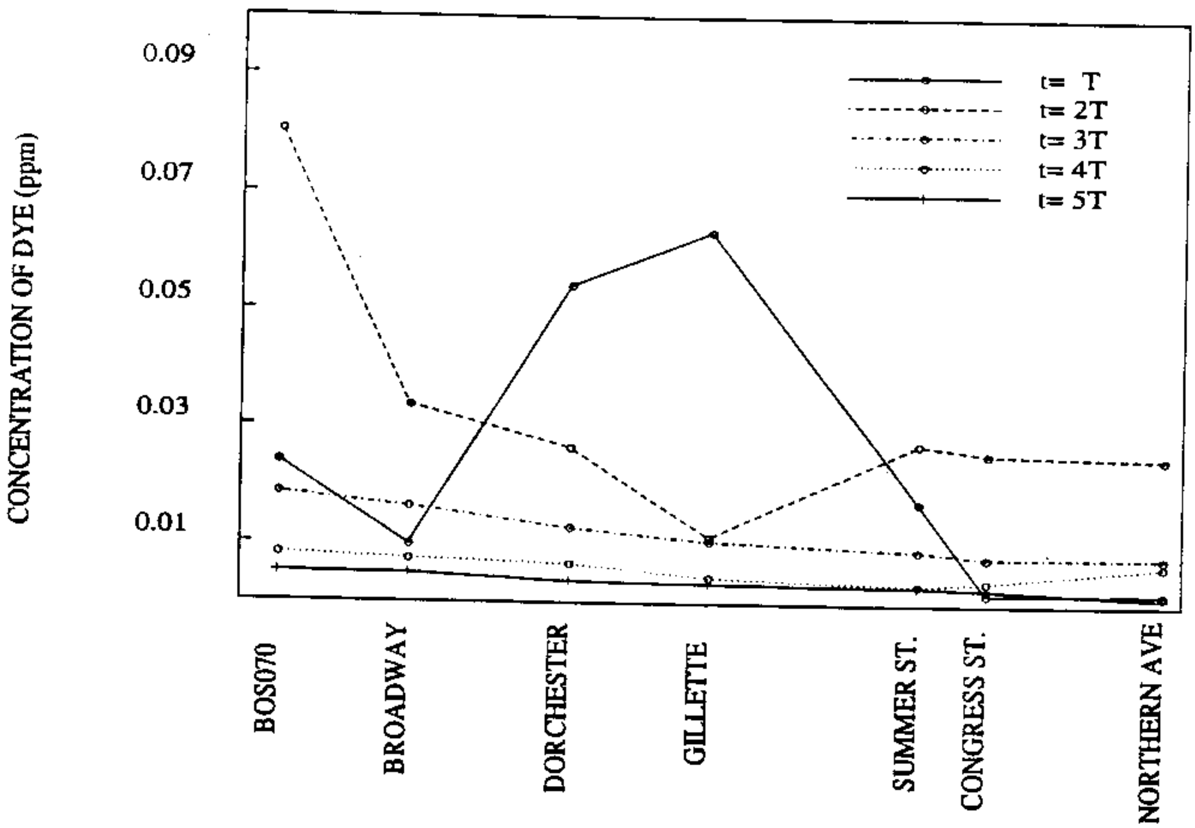

Figure 34. Dye concentration in FPC, July 1990

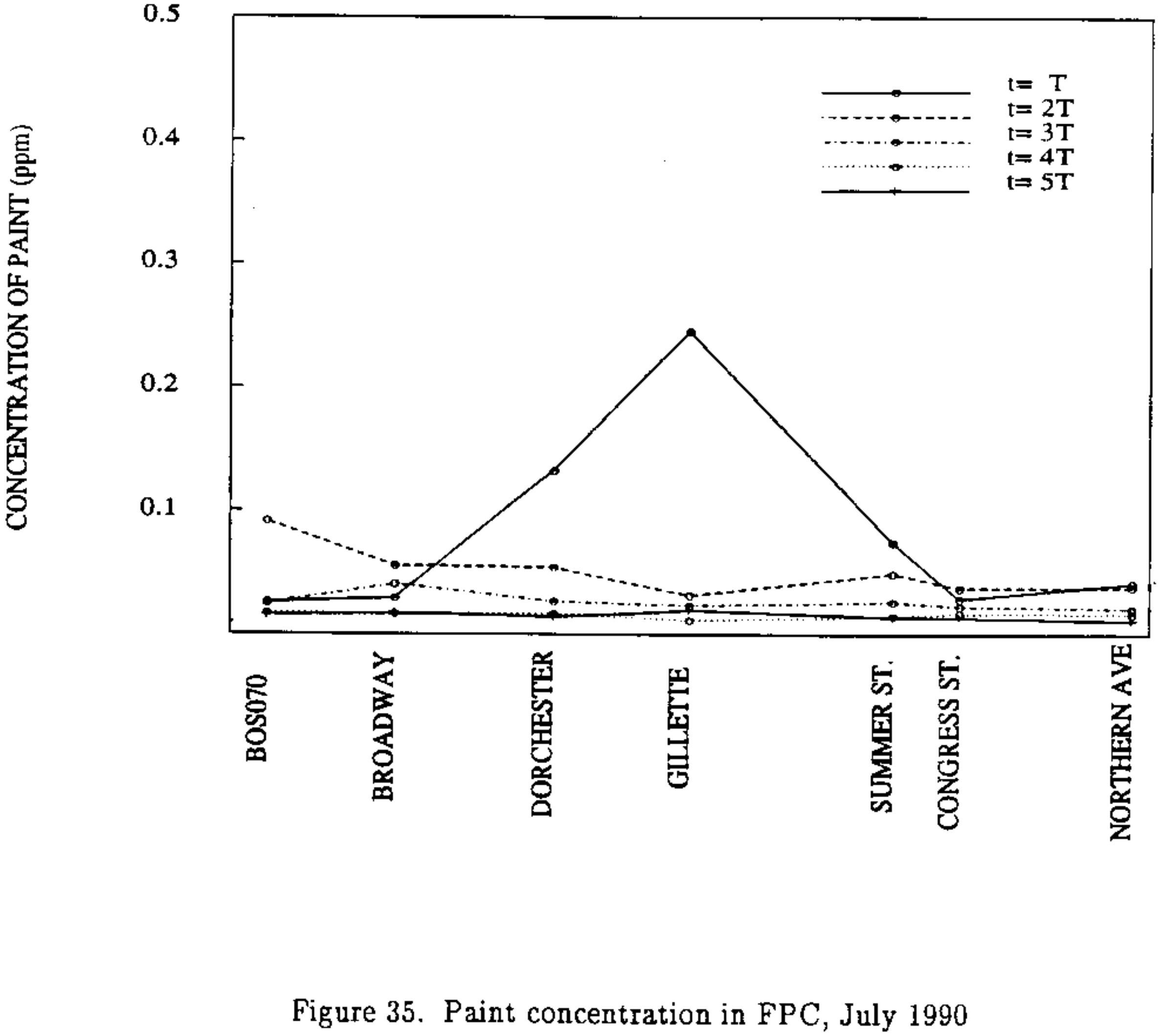

Figure 35. Paint concentration in FPC, July 1990

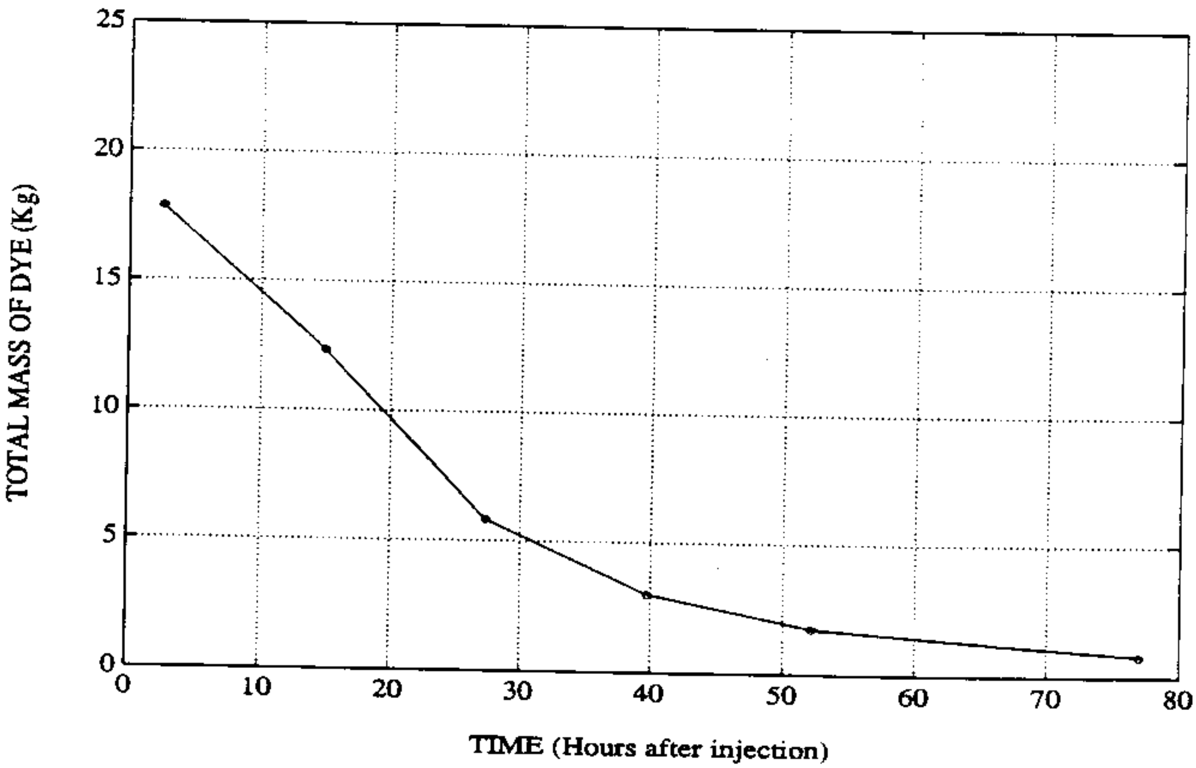

Figure 36. Dye mass vs. time, July 1991 study

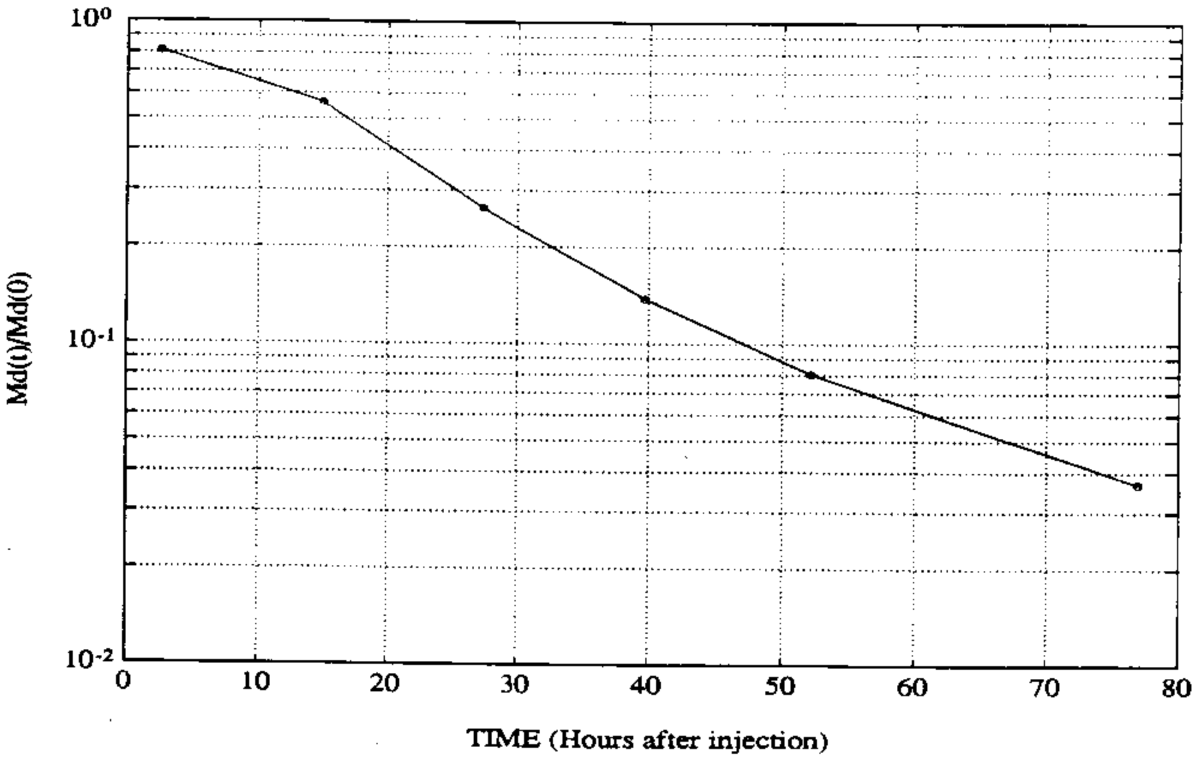

Figure 37. Normalized dye mass vs. time, July 1991 study

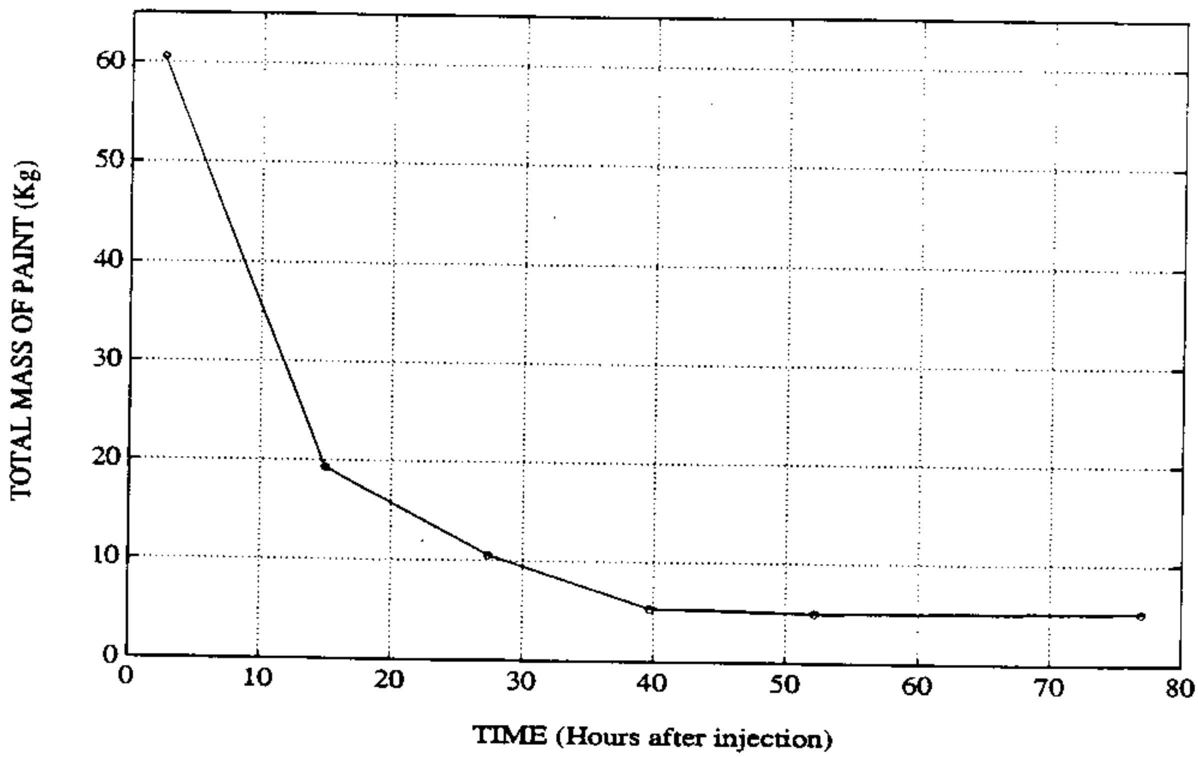

Figure 38. Paint mass vs. time, July 1991 study

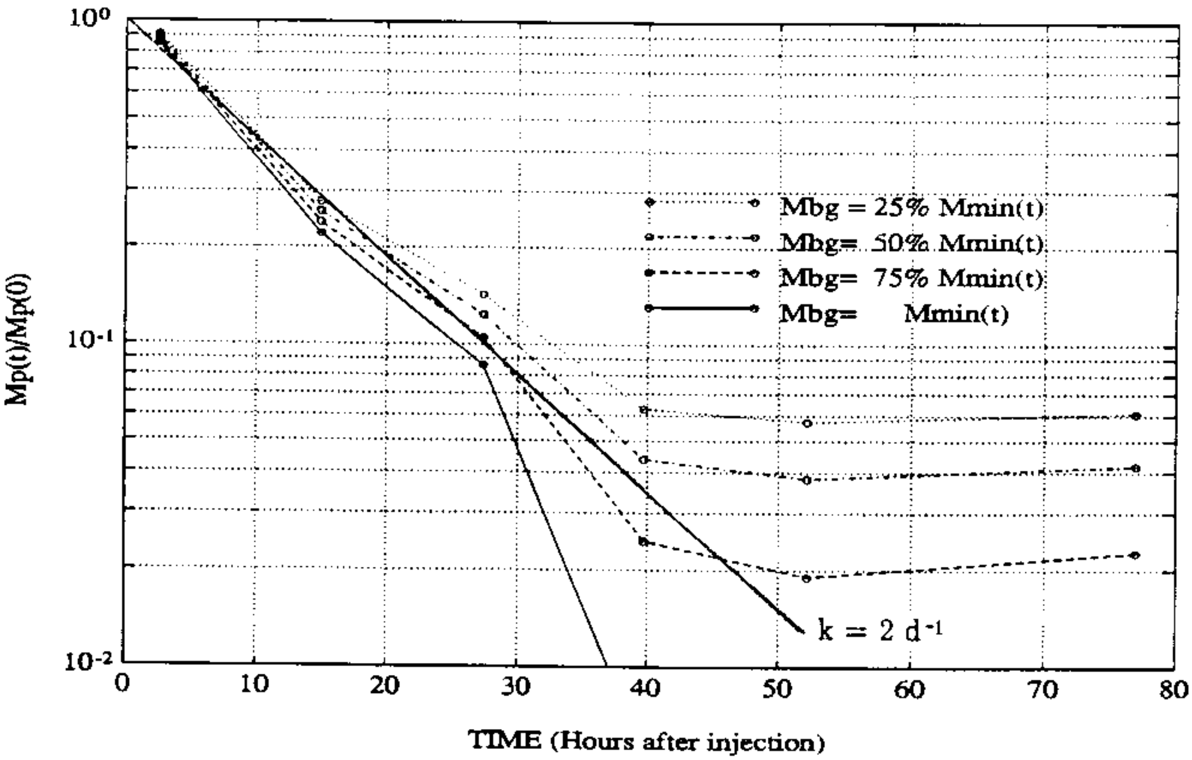

Figure 39. Normalized paint mass vs. time, July 1991 study. Different curves reflect different assumptions on background paint concentration.

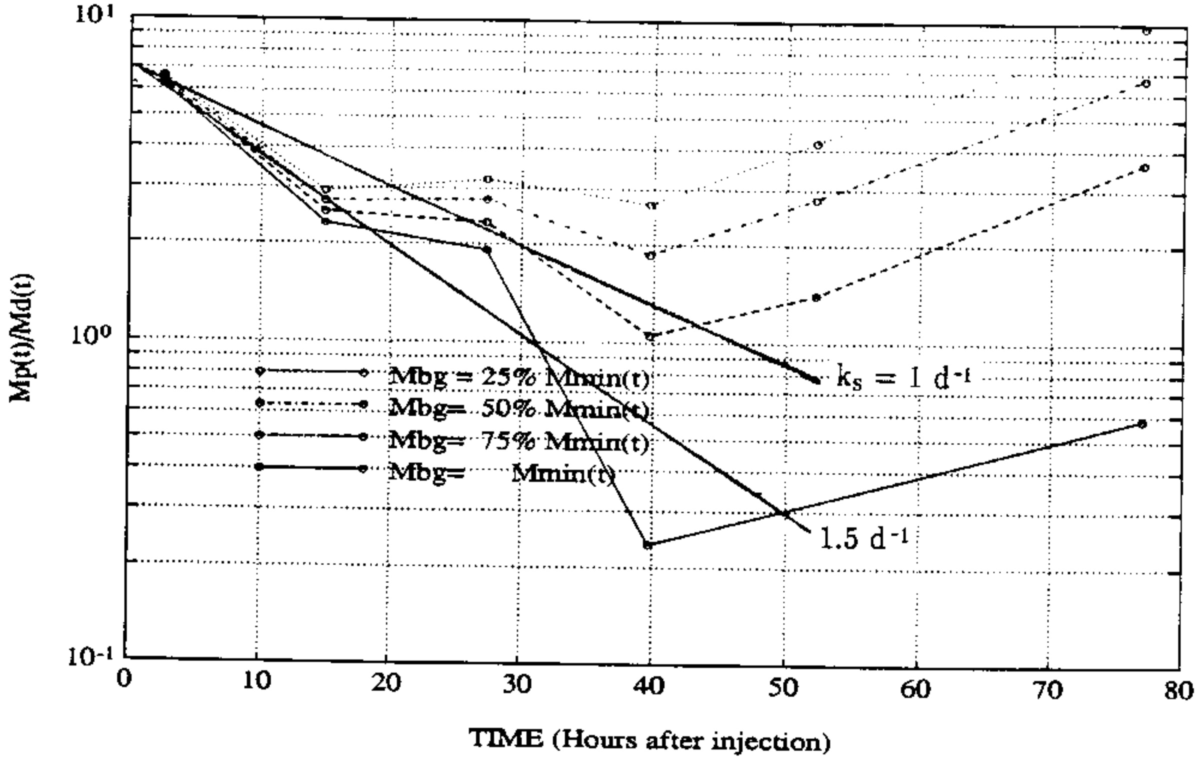

Figure 40. Ratio of paint mass to dye mass vs. time, July 1991. Different curves reflect different assumptions on background paint concentration.

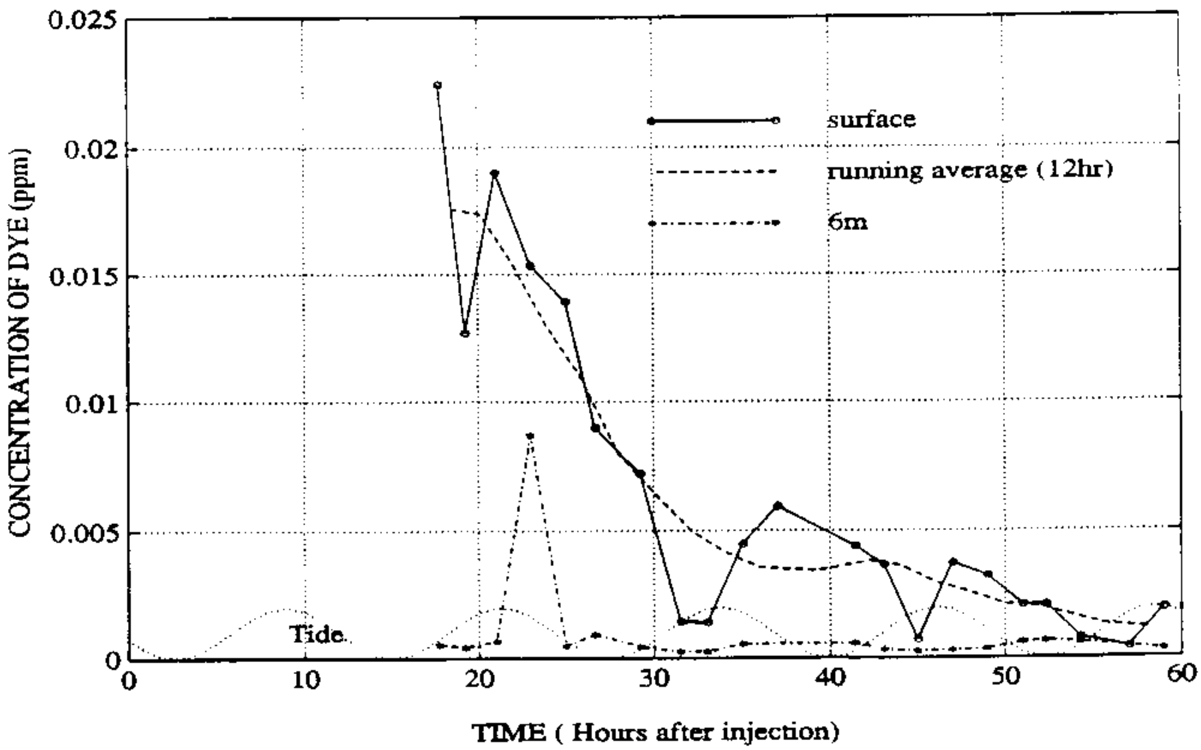

Figure 41. Dye concentration at Northern Avenue vs. time, July 1990

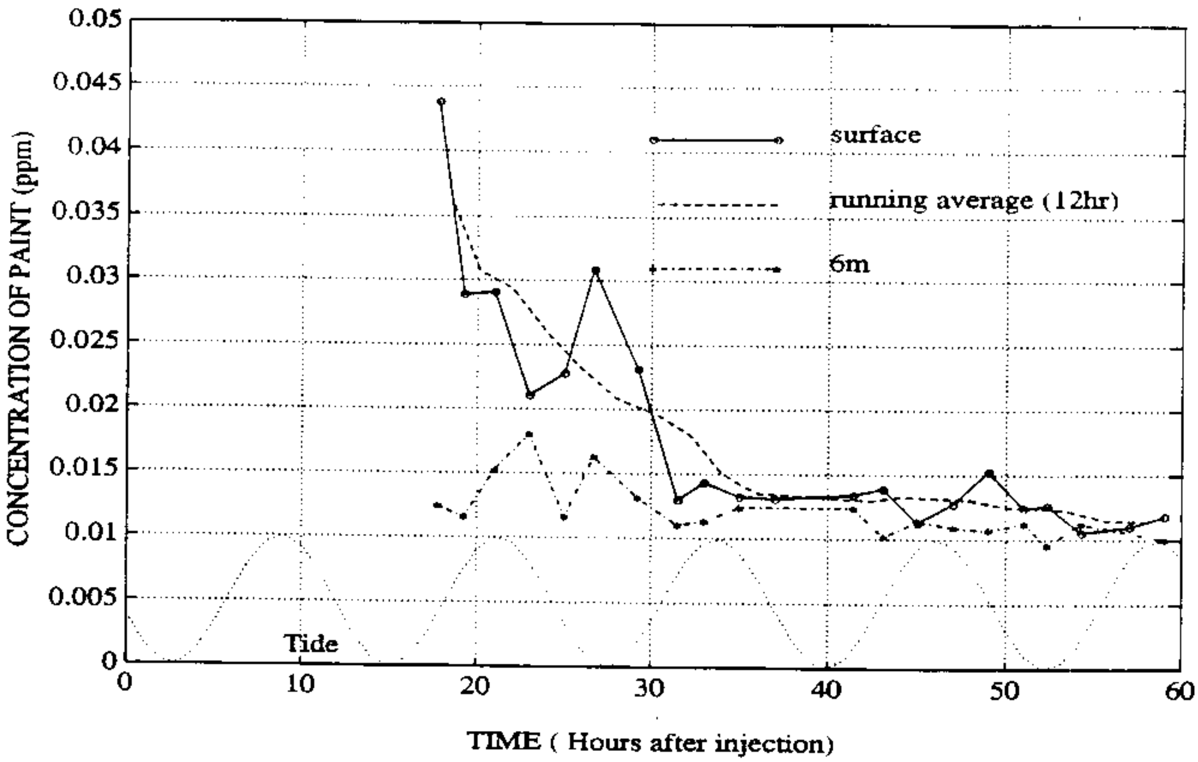

Figure 42. Paint concentration at Northern Avenue vs. time, July 1990

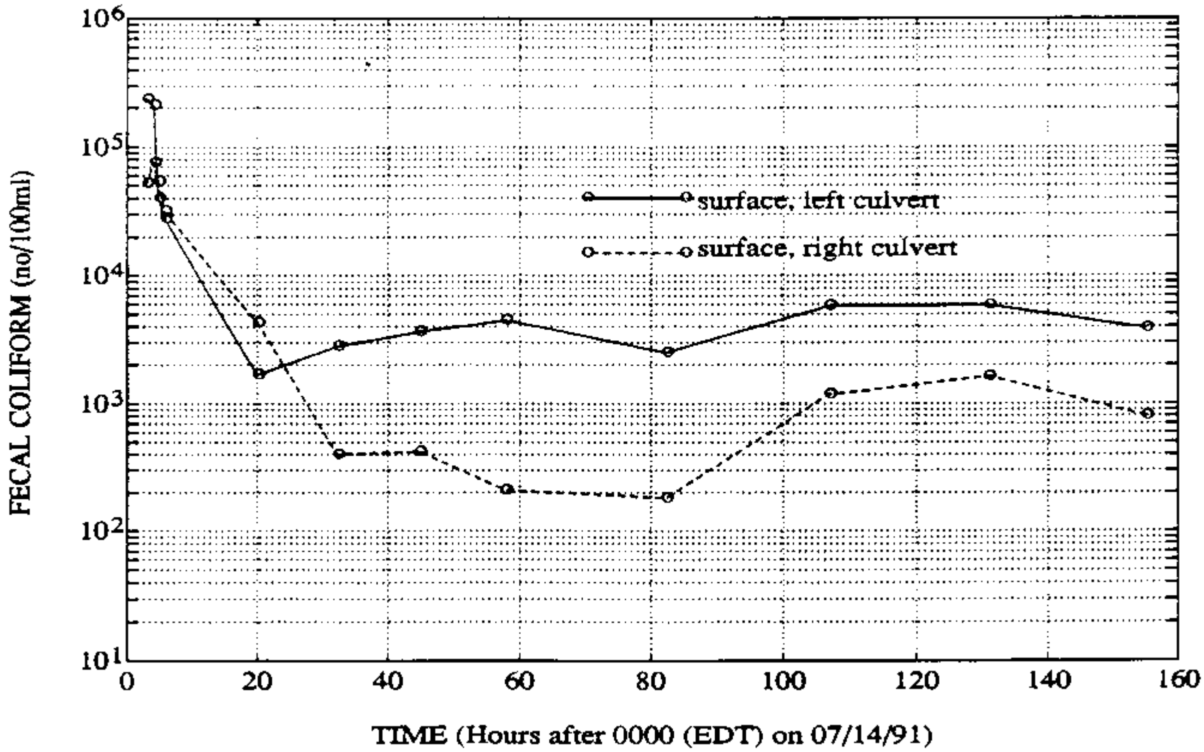

Figure 43. Fecal coliform near outfall during july 1991 survey

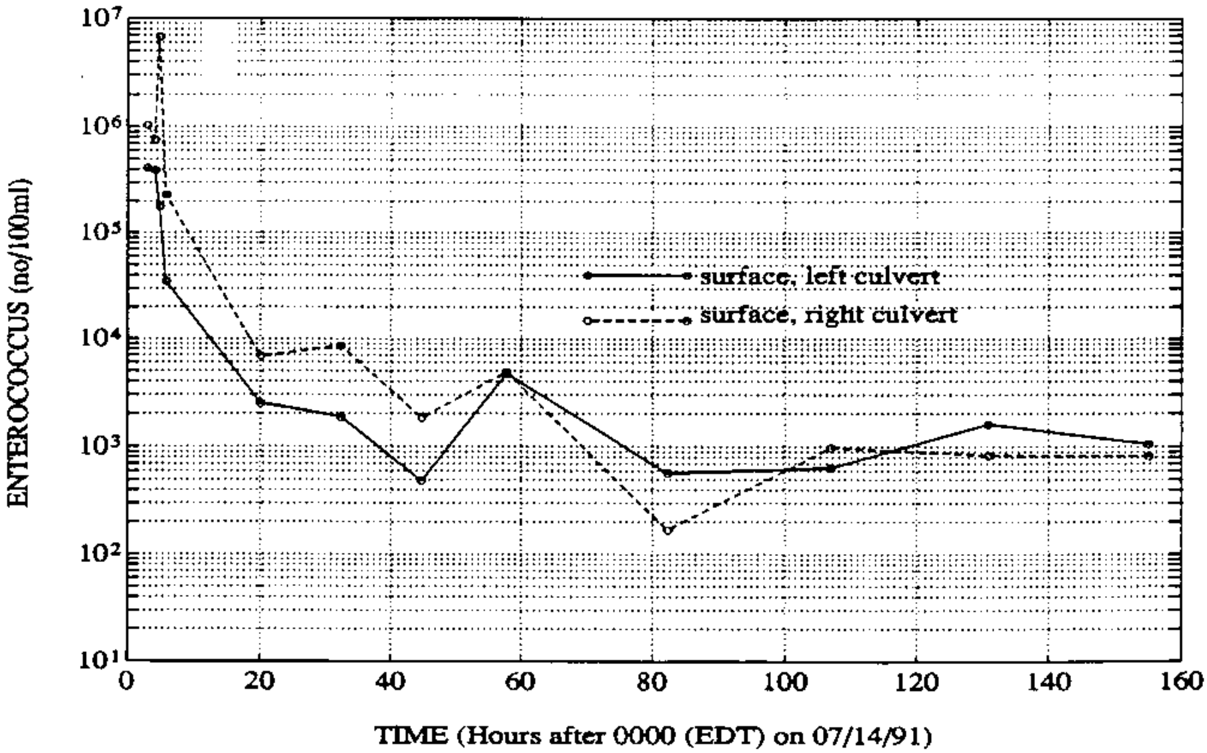

Figure 44. *Enterococcus* near outfall during July 1991 survey

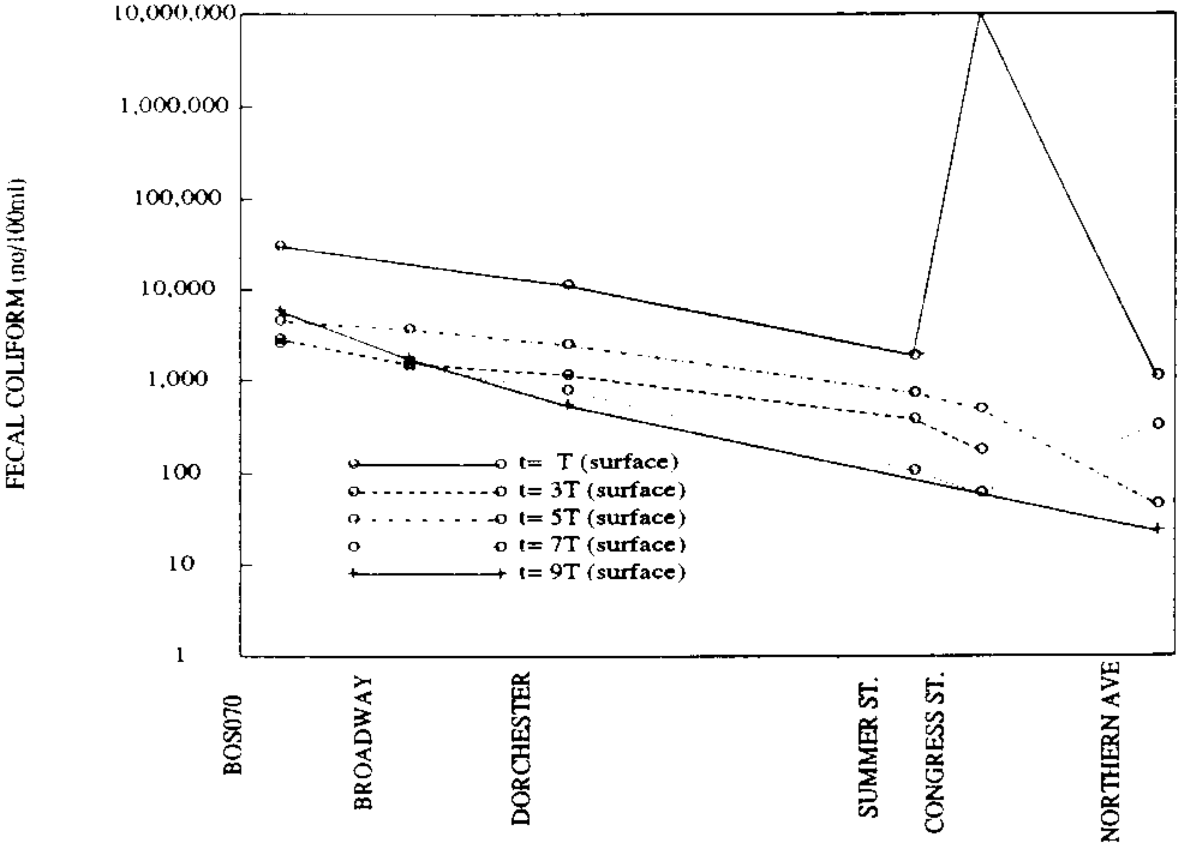

Figure 45. Fecal coliform levels in FPC, July 1991

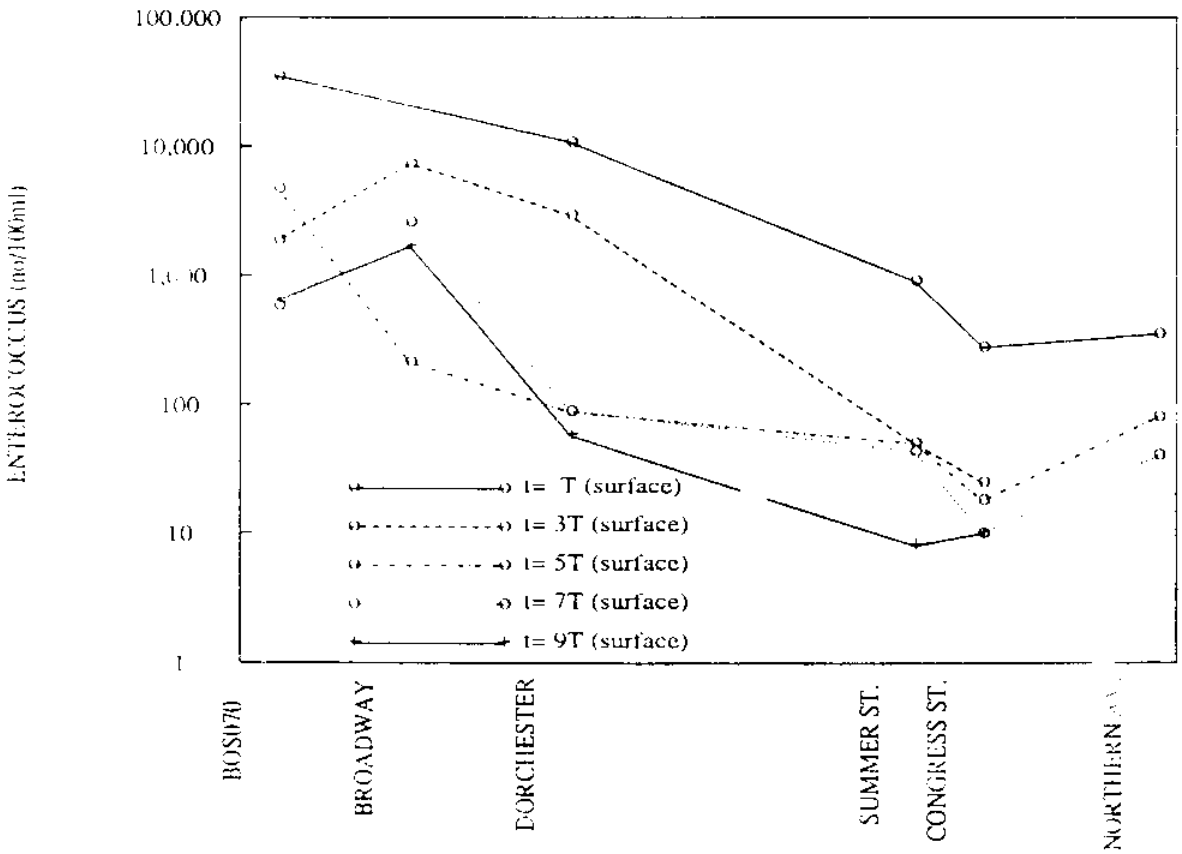

Figure 46. *Enterococcus* levels in FPC, July 1991

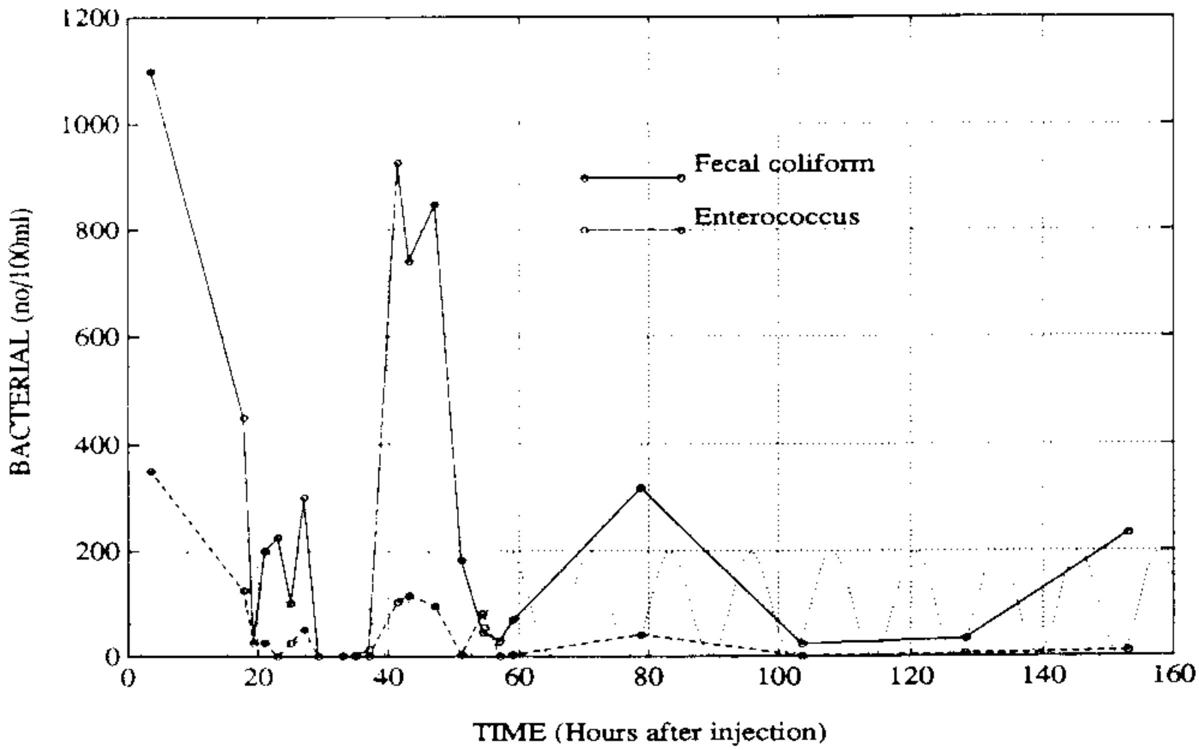

Figure 47. Bacteria levels at Northern Avenue vs. time, July 1991 study

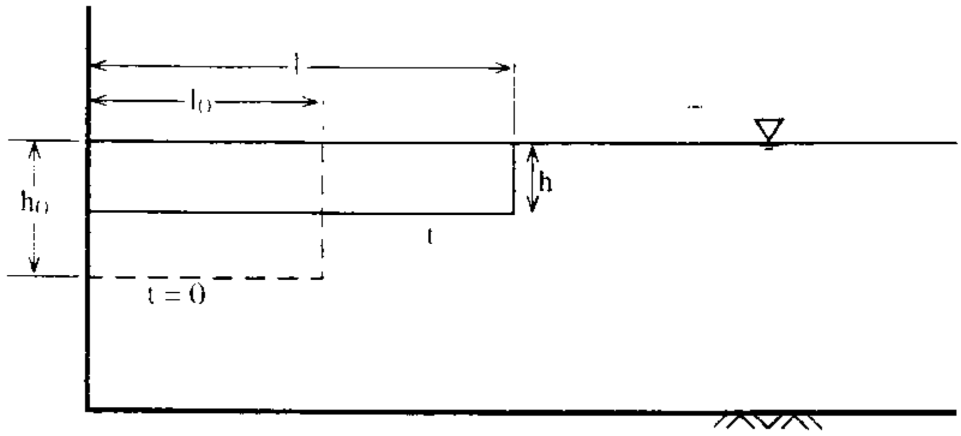

Figure 48. Definition sketch for analysis of density currents

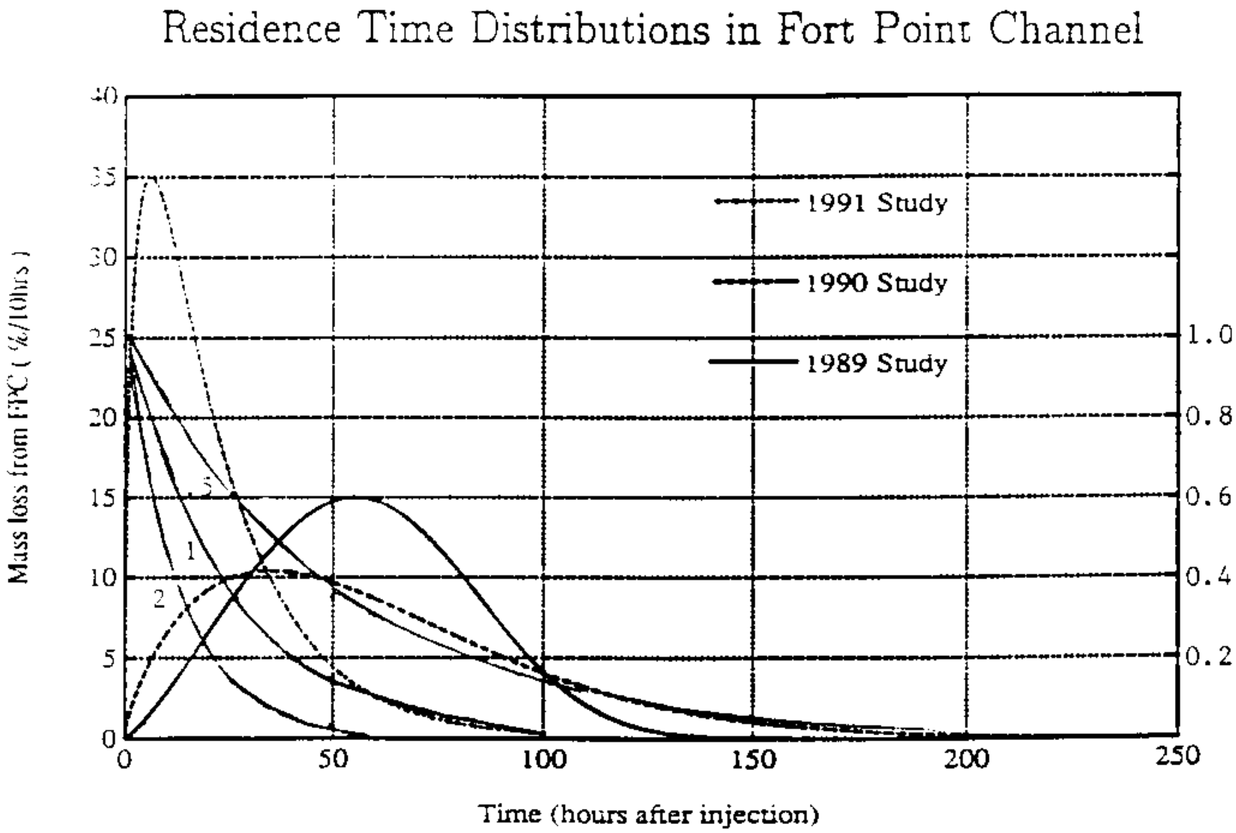

Figure 49 Residence time distributions in Fort Point Channel (left ordinate). First order (exponential) decay curves for rates of 0.5, 1.0 , and 2.0 d^{-1} (right ordinate)

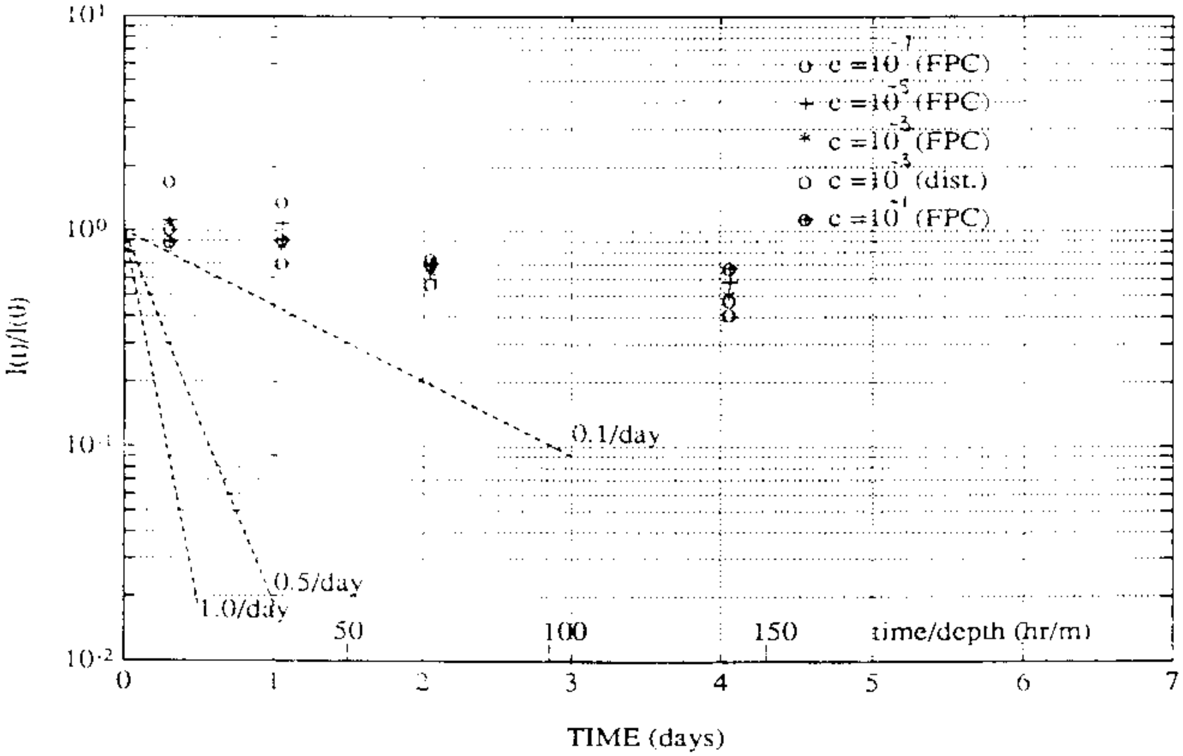

Figure 50. Fluorescence intensity versus time for laboratory settling tests

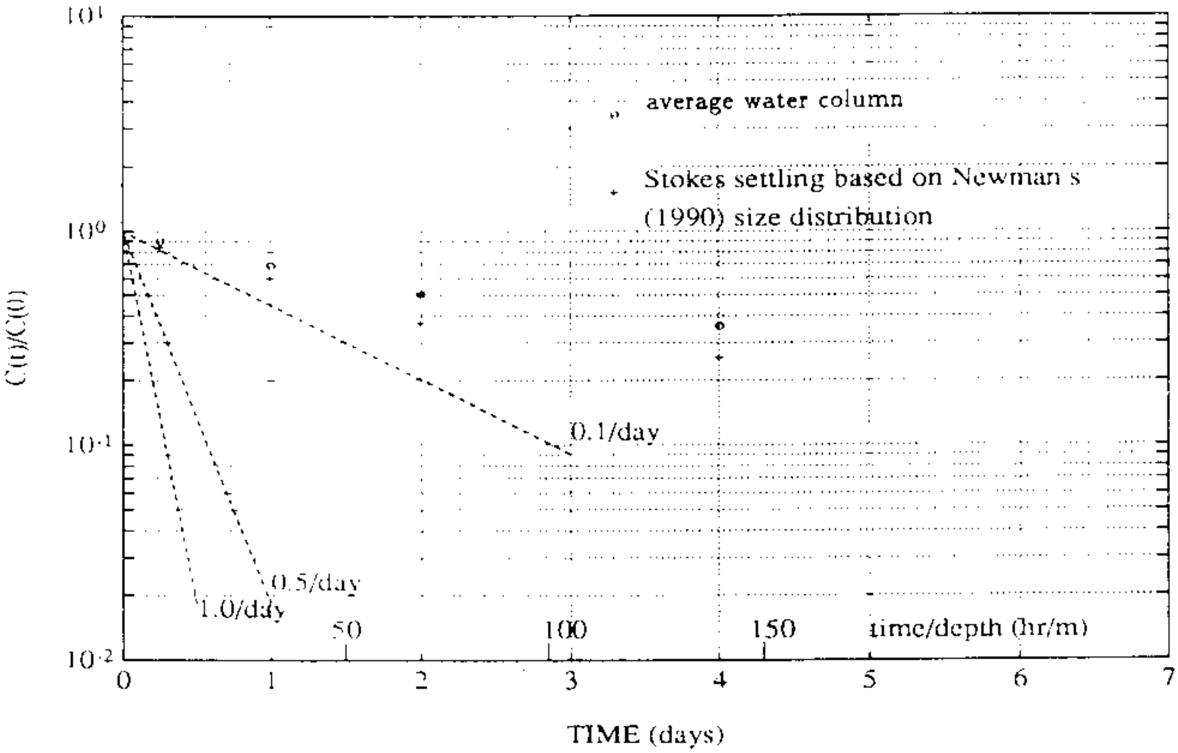

Figure 51. Suspended paint concentration versus time for laboratory settling tests

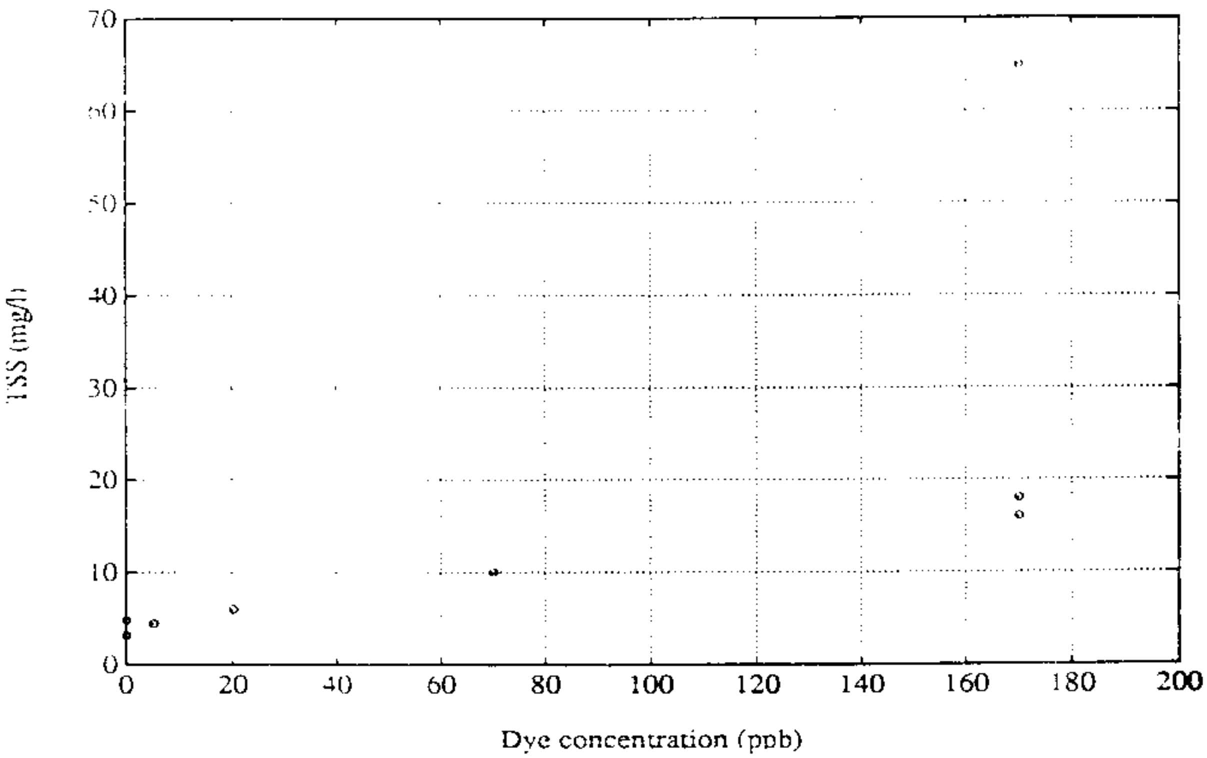

Figure 52. TSS vs. dye concentration (measured near boil)

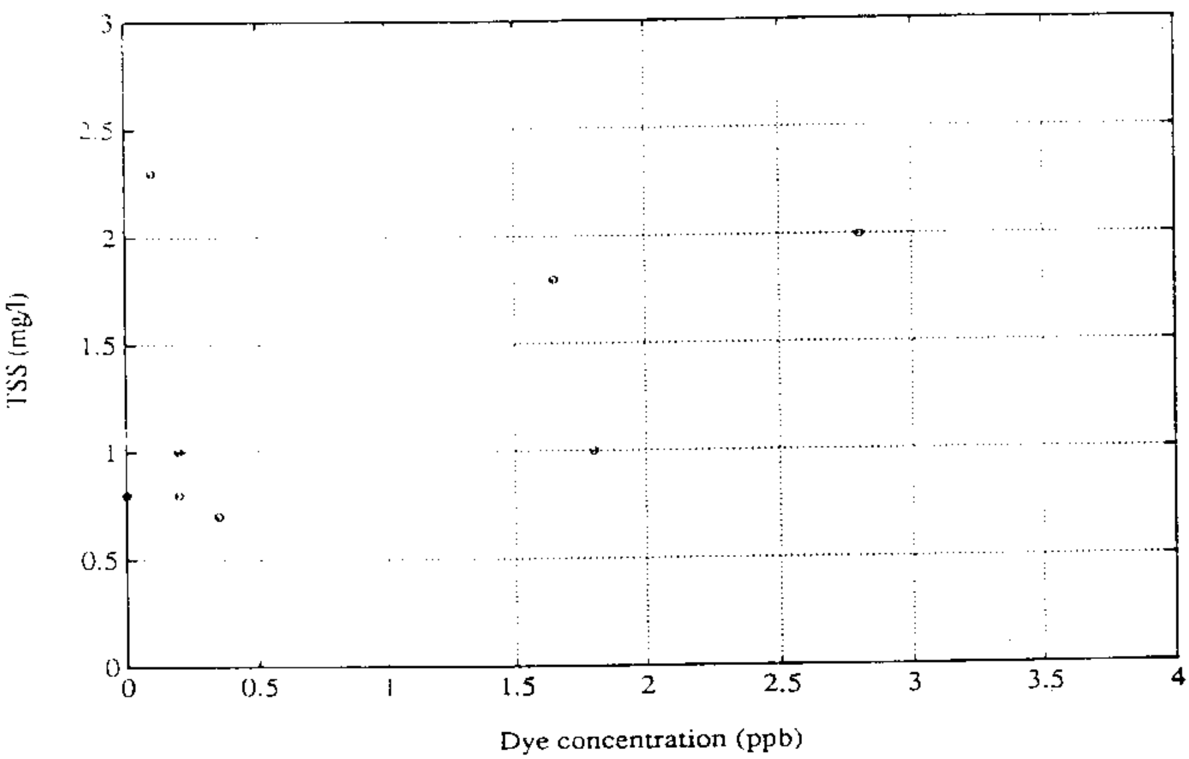

Figure 53. TSS vs. dye concentration (measured downstream)

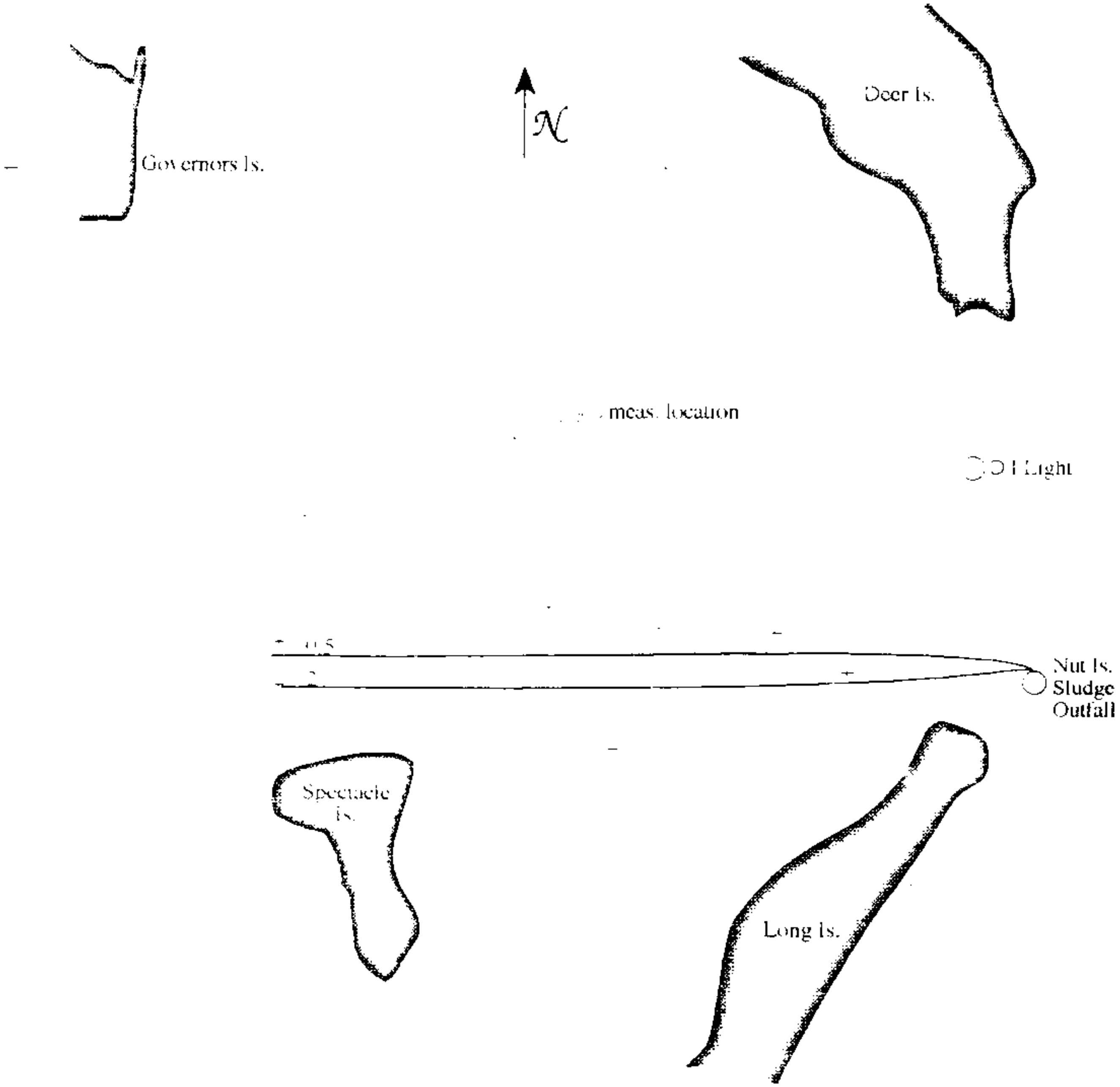

Figure 54. Near surface dye concentration (ppb relative to initial dye [illegible]) measured between 1610 and 1700 EDT on July 31, 1990

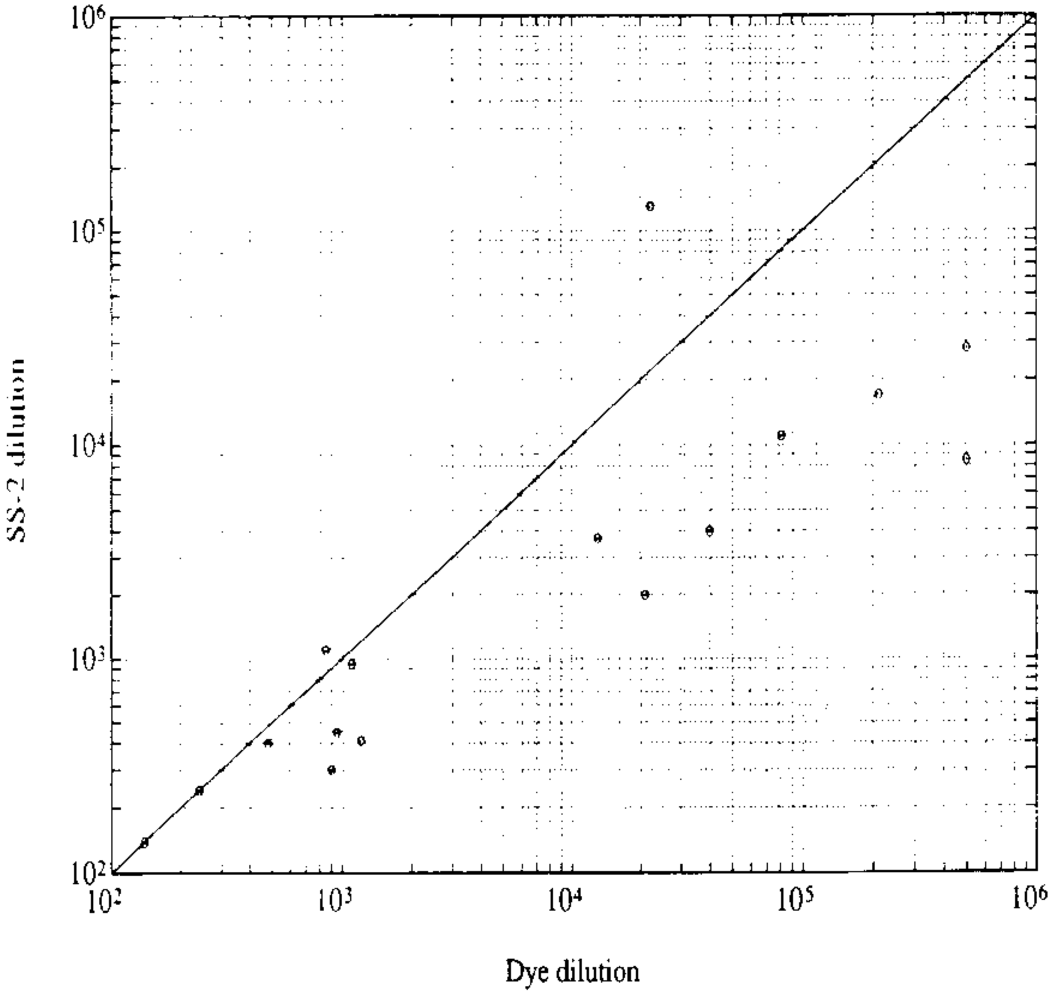

Figure 55. Suspended solid dilution vs. dye dilution (Nut Island) Oct. 1990

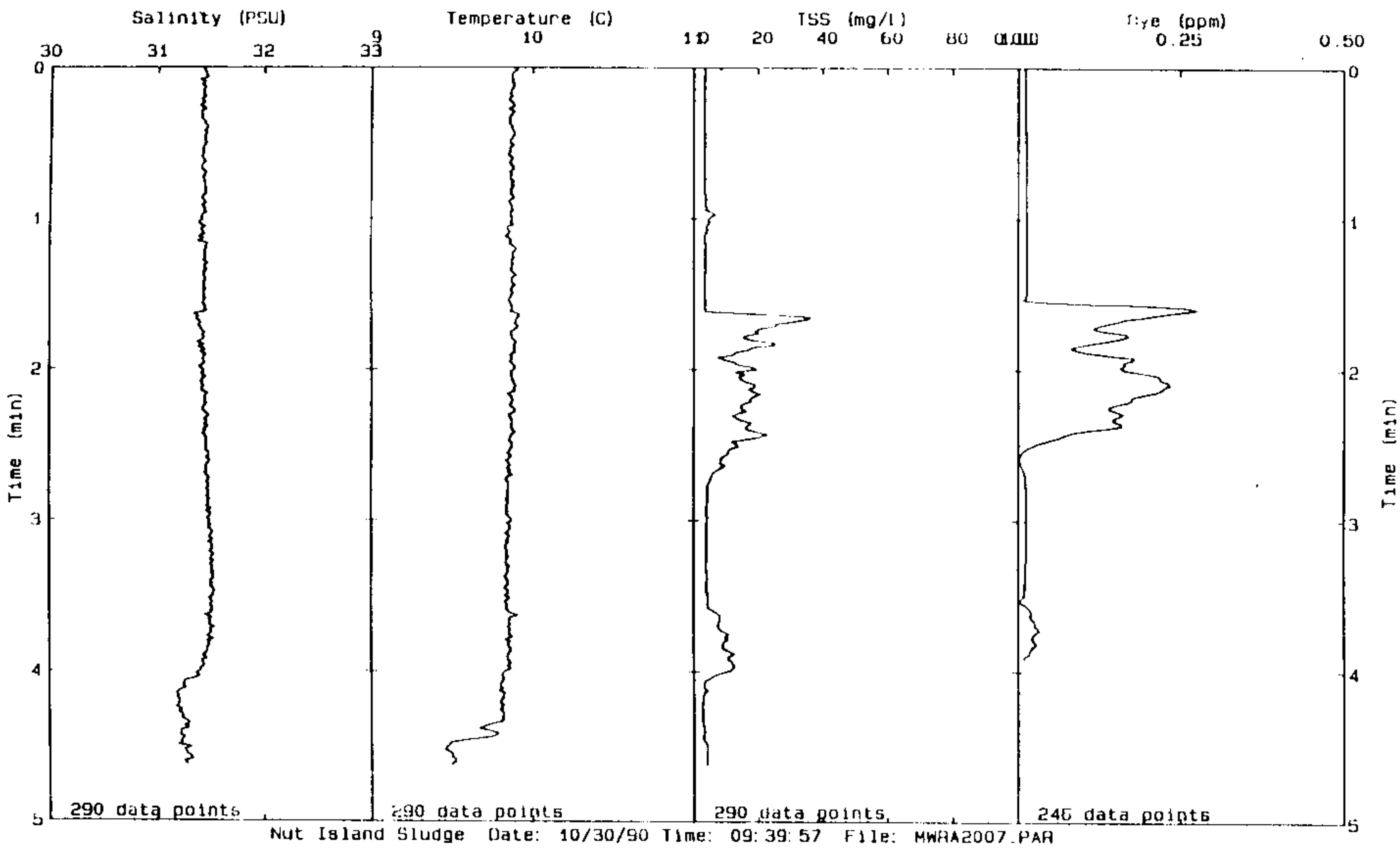

Figure 56. Time series dye and TSS measurements near Nut Is. sludge discharge (from Battelle, 1991)

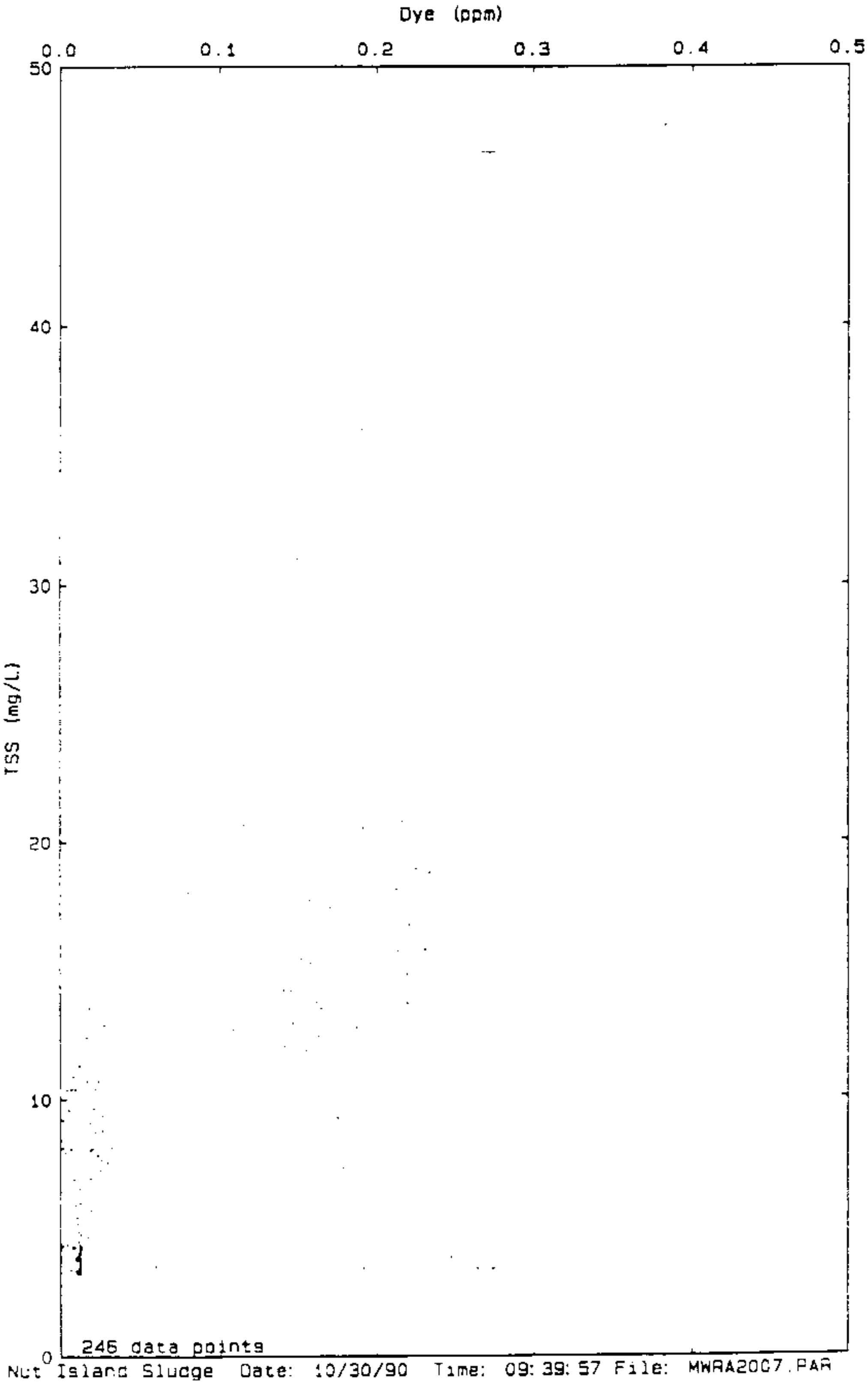

Figure 57. Correlation of dye and TSS concentrations corresponding to Figure 56